DrawinG CONNECTIONS: NEW DIRECTIONS IN DRAWING AND COGNITION RESEARCH

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Abstract

How is our understanding of the interactions between drawing and cognition expanding, and how is this enabling new directions in drawing research and development? What might expert drawers know and be able to do, sometimes unconsciously, that could benefit others in a variety of domains, including education and STEM professions?

The paper reviews research surrounding the emerging field of drawing and cognition studies; outlining its current scope, summarising key pieces of research and their relationships. We report on research activity connected to the 2011/2012 symposium *Thinking through Drawing,* and also consider related research that touches on the same agendas.

We argue that a growing cognitive understanding of drawing is producing knowledge and practical outcomes relevant across many arenas. In particular, we consider educational applications of this new knowledge, extending beyond drawing instruction to potential new contributions in, for example, the training of surgeons and in the development of general cognitive skills.

Future research directions are identified, and questions pertaining to the emerging issues and potential contributions to be made in the coming decades are posed.

# Introduction: drawing connections

 “Drawing is a fundamental and cognitive activity of the human mind, one that stretches across many and diverse subject domains… lines and marks on surfaces are ways of having and constructing ideas equally as they constitute ways of expressing them.” Judith Burton (2011: 4)

Advancing technologies and theories in cognitive science are shifting assumptions about the nature of perception and cognition, leading to a re-framing of our understanding of drawing. Contemporary interdisciplinary methodologies for studying drawing, including practice-based approaches, are raising new questions about the position of drawing in research in many disciplines, and the role of visualisation and ‘creative thinking’ in scientific enquiry. This paper reviews emerging issues in drawing and cognition, many of which have been presented at the symposia *Thinking through Drawing*. The paper also suggests potential future directions in drawing and cognition research, highlighting areas for further enquiry.

Human brains knit together a functional, unified vision of a stable external reality through a multitude of tiny acts of attention to a wide variety of sources. Perception, past experiences, and other sensory information, such as the movement of our bodies in space and inner awareness of our own heartbeat, influence what we see and notice. Neuroscientists do not yet fully understand the complex mechanisms which make these acts of cognition possible, yet the specific patterns of connections each of us make between present experiences and prior knowledge define who we are as individuals. Drawing, because of its immediacy and simple, accessible materials, is a particularly good reflection of the human brain and mind in action.

Drawing can be understood as the visible trace of our cognitive processes, the record of how we perceive, understand and process our experiences not just with our brains, but our hands and bodies as well. Drawing allows us to play with our thoughts outside the confines of our minds. Artists, architects, mathematicians, engineers and other professionals draw to explore ideas and discover new ones. Drawing visual explanations of scientific processes can enhance learning, and drawing projects can develop numeracy. The drawing process enhances attention and memory more powerfully than words alone and may communicate many ideas better than language.

Drawing is an activity that occurs in many areas of human endeavor beyond art and design. It is used to extend working memory, visualise, test hypotheses, de-construct and re-construct concepts, make comparisons, solve problems, as well as to communicate to others. Theories of situated and embodied cognition allow a more comprehensive understanding of the role of perceptual processes underlying abstract thought, highlighting the importance of the hand and eye. In this context, drawing is understood as more than the mere reflection of our mind at work. Rather, it is a highly useful means to externalize and extend mental processes as they occur. This perspective sheds new light on the purposes and potential applications of drawing in the arts, industry and education.

The *Thinking through Drawing* symposia position practitioners, theorists and researchers of drawing in parallel, who demonstrate that cognitive scientists’ research findings are often in sync with practitioners’ intuitive and sometimes poetic assertions about the nature and purpose of drawing. This suggests new opportunities to involve artists in scientific enquiry, and raises questions about the potential of tacit forms of knowing to inform research more generally. The symposia offer examples of diverse and hybrid methodologies in which the role of artists varies, as subject matter, collaborators, drivers and consumers of research, illuminating the potential of interdisciplinary enquiry in this arena.

## New ways of thinking about thinking, and thinking through drawing

Innovations in cognitive science (based on the neural and psychological roots of abstract reasoning, belief formation and ideation) provide an opportunity to rethink the nature of drawing. Recent theories of grounded, embodied and situated cognition have transformed our understanding of perception, and studies investigating the interplay between perception and conception in the drawing process are complementing these insights. The implicit, tacit knowledge of those who draw can be acknowledged in the context of a better understanding of the interplay of perception and cognition.

**Grounded Cognition**

Our capacities for abstract reasoning and logic are dependent on sensory input systems such as vision and spatial awareness. Research in cognitive science over the past twenty years has revealed how higher order thinking processes function across these systems, by recruiting neural substrates dedicated to internal and external sensory data. Developmental neuropsychologist Usha Goswami points to the role of shared neural networks in cognition (2002) citing behavioural and neurological evidence. In her review of research on young children’s analogical capacities (1992, 2001, 2002) Goswami describes how our ‘knowledge representation is rooted in attention to the perceptual structure of objects and events’ (2008: 51). For example, the foundation of our cognitive framework for anticipating and representing the behaviour of objects is shared with that of the behaviour of people. She goes on to relate sensitivity to space, objects and causal relations to more abstract cognition such as conceptual representation, memory, logic, and the concept of agency in others (see also Leslie 1994). Further evidence supporting these claims lies in the shared neural loci of experience for percepts and concepts.

Perception and conceptual understanding are not only intimately bound, but are, in a sense, the same capacity. This insight throws new light on the potential of drawing as a particularly useful vehicle of joint perceptual and conceptual inquiry. It also re-frames notions of the broader benefits of drawing practice, as a development of observational, analytic and visualisation skills.

We use metaphors based on our physical experience of being in and moving through the world to describe abstract concepts. Cognitive linguists George Lakoff & Mark Johnson discuss how shared neural loci (of experience and concepts) are the basis for metaphor (1980; 1999). Johnson explains how ‘meaning and thought emerge from our capacities for perception, object manipulation, and bodily movement’ (2007: 113 see also, Johnson 1990). The neural ‘body in the mind’ reconstructs tactile, spatial and visual experiences to ‘make sense’ of more abstract ideas. An idea can be conceived of as slippery, fragile, liquid, heavy, difficult to grasp, thrown or bounced around. Ideas can be held lightly, built up and then shattered, attacked and defended. Similarly, Douglas Hofstadter (2001) declares that ‘analogy is the core of cognition’, ‘the shift is to suggest that every concept we have is essentially nothing but a tightly packaged bundle of analogies, and to suggest that all we do when we think is to move fluidly from concept to concept.’ (Hofstadter 2001: 500).

**Drawing as embodied cognition**

“The lines can stand up straight, lie down flat, circle around, scribble around, wiggle and jump, scrunch up, be rough or gentle, be thick or thin, and have any variety of relationships with other lines. Each line is an idea in itself, with a beginning, middle, and an end – just like us.”
(Michael Moore 2011: 35)

Cognitive psychologists, such as Susan Goldin-Meadow (2003), are showing us how what we imagine as our minds, are much more than our brains. The internal awareness and movement of our bodies, and our gestures, those ill-defined yet surprisingly essential hand movements that accompany speech, help us navigate through concepts and understandings not yet completely within our grasp (see also Kontra, Goldin-Meadow & Beilock, in press; Goldin-Meadow & Alibali, in press). Drawing can be understood as the visible trace of the ways in which we think, not just with our brains but with our hands and bodies as well. These traces of awareness, action and movement, even in the finished drawing, allow viewers to intuit this process and follow along the drawer’s journey. Chris Moffett suggests that, in this way, attention can be thought of as ‘a way of drawing’ and a “way of moving” (2011: 135): “a gesture leads to a mark, which can only be understood and transformed by another gesture. The action of looking at a drawing is not a kind of abstract empathy or decoding, but is itself a way of moving, of drawing (2011: 239).

Tversky & Suwa (2009) discuss how sketches can be used to convey concepts that are both literally, and *metaphorically* spatial (a map represents actual spatial relations, while a diagram representing a research project as a journey, for example, uses a spatial metaphor to describe a conceptual process). That many abstract concepts are understood through spatial metaphor indicates the relationship between spatial (and visual, tactile, motor, etc.) cognition and ‘core cognition’ (our faculties for reasoning and higher order thought). The embodied paradigm means that metaphor and analogy, previously considered linguistic devices, are now understood as the product of a cognitive system that utilises the senses for abstract reasoning. These metaphors may be revealed linguistically, or through gesture (see Williams 2008 for a further discussion of metaphor and gesture), and of course, by diagrammatic reasoning and even doodling. As Tversky notes, “Lines, straight or messy, serve our behavior and our thought” (2011: 15).

At the 2011 *Thinking through Drawing* symposium, David Kirsh reviewed some of his research investigating visualisations as situated cognition. His studies comparing the effects of visual aids on performance in a game of tic-tac-toe, demonstrated that when viewing an image of an empty grid, people performed better (i.e. faster), when working with complex 4 by 4 and 5 x 5 grids (2011, see also Kirsh 2009). Kirsh also analysed how gesture is used by professional dancers to enhance learning of movement sequences. Dancers often rehearse by ‘marking’ parts of a routine as they are learning, in a kind of gestural shorthand (2011, see also Kirsh 2010). Kirsh’s studies are valuable in determining the limits of our cognitive abilities and measuring the extent to which visualisations can extend our cognitive capacities. This is in keeping with Tversky’s (2011) assertions about the role of gesture in thinking and internal reasoning (as well as communicating). The role of the hand was also highlighted by Angela Brew’s research, which compared patterns of eye and hand movements as drawing skills were learned over time. Brew’s study points to the cognitive role of the hand, positing that the hand can no longer be thought of as led by the eye during drawing; rather it plays an active part in perception.

**Drawing as situated cognition**

“For me, drawing is a way of seeing things that don’t exist yet. I draw to discover what I am thinking — to see how it looks — to flesh it out”. (Fitch 2011: 147)

“Drawing is a way of working out ideas. It has an inherent quality of expedience and clarity”. (James Esber, in Kantrowitz, Brew & Fava, 2011: 115)

Psychologists’ accounts of drawing, stemming from empirical and observational studies of drawers, offer us cognitive and executive models of drawing as situated cognition. Suwa & Tversky’s (2003) work, for example, observes the way perceptual and cognitive processes interact during drawing. The way sketches, and other external representations, act as a cognitive tool for extending memory and thinking has been discussed widely (e.g. Newell & Simon, 1972; Tversky, 1995, 2001; Kirsh, 1995; Norman 1993; Tversky & Suwa, 2009). Suwa & Tversky describe sketching as a two-fold process (see also Goldshmidt 1994; Schon 1983; Arnheim, 1969) “as an external tool for checking the coherence and appearance of ideas” (2003: 1140) and for “generating new ideas and interpretations” (2003: 1140). They describe how these two processes work in a ‘productive cycle’, citing examples of architects and designers (see also Suwa & Tversky, 1997; Suwa, Gero & Purcell, 2000; Suwa, Tversky, Gero & Purcell 2001; Gero, Tversky & Purcell, 2001).

Suwa & Tversky, define the skill of ‘constructive perception’ in their study of architecture students and experts (2001). They showed that as expert architects sketch, they look for “the coherence and appearance of ideas” and generate new interpretations based on possibilities raised by the ambiguity of the sketches. New ideas are generated by “[r]egrouping elements, by changing reference frame, and by altering perspective” (2003: 1141), enabling architects and others who sketch to visualise and ideate to avoid the ‘fixation effect’ (Howard-Jones, 1998) in which the rate of generating new interpretations reduces rapidly after a few minutes. Performance in generating a large number of interpretations of an ambiguous drawing can therefore be a measure of skill in constructive perception. While this skill is important to design, they propose that it may also be generalisable to problem solving and ideation in other domains (Suwa & Tversky 2002; 2003).

An exercise in constructive perception was carried out at the New York “Thinking through Drawing” symposium by Ian McInnes, who knitted his response to the proceedings as they were happening. He described how “the process of making and the qualities being developed took on their own momentum and context. There was a point at which the activity took over and started to reveal interesting qualities in their own right, which in turn informed further work” (2011: 133).

The psychological evidence and explanations we now have of how cognition is grounded in physical experience, allow us to demonstrate why drawing is a powerful way of thinking across the board in many ways. Validating assertions that artists have been making for some time, and bringing to the forefront the broader importance of the kinds of thinking engendered by arts education. While these ideas in psychology are now well established, we seem to be only beginning to explore the untapped potential of drawing that these ideas point to.

These theories were informed by observations of drawing practitioners. Therefore it can be said that the studies are not generating new knowledge, but exposing knowledge that is already held, tacitly, by those artists and designers studied.

**Artists as experts in ‘thinking through drawing’**

“Through science we know that all of our mental life arises from the activity of our brain; thus by observing that activity we can begin to understand the processes that underlie our responses... Art on the other hand, provides insight into the more fleeting, experiential qualities of mind, what a certain experience feels like. A brain scan may reveal the neural signs of depression, but a Beethoven symphony reveals what that depression feels like. Both perspectives are necessary if we are to fully grasp the nature of mind, yet they are rarely brought together.”
Eric Kandel, (2012: xvi)

“If an object, idea, daydream, pattern, place, or experience can be drawn, it makes more sense to me, and can verify that I have experienced it.”
(Moore 2011: 35)

Seeley and Kozbelt’s recent research investigating artists’ perceptual abilities, demonstrates that they do, indeed, ‘see differently’. By logical extension, from the embodied paradigm we might infer that they also ‘think differently’. This is supported by Seeley & Kozbelt, who demonstrate how artists’ perceptual skills confer “an advantage in visual analysis, which consists of the ability to focus attention on sets of stimulus features” and enable ‘attentional strategies’ that “enhance the perceptual encoding of stimulus features diagnostic for the identity of objects and inhibit the perception of potential distractors” (Seeley & Kozbelt 2008: 153; see also Kozbelt, 2001; Kozbelt et al., 2010). These ‘perceptual advantages’ are measurable through psychometric testing.

Similarly, the authors’ own research identifies artists’ metacognitive skills. These include the ability to postpone judgement, managing evaluative processes within strategic patterns of attentional activity (Fava 2011) and the ability to synchronise movement, to develop fine control of motor skills, and enhance bodily engagement with the world (Brew 2011). Furthermore, Kantrowitz’s research demonstrates the capacity of drawing to enable greater self-reflection and emotional control in young people, as well as facilitate a process of discovery for both novices and experts (Kantrowitz 2011, 2012).

While these studies may be considered simply proof of something artists themselves have long been claiming, it is nevertheless valuable as a basis for further empirical testing and theorising in cognitive psychology. These findings may also contribute to informing debates around the holistic benefits of drawing practice, which benefit from concrete examples. In light of these new cognitive accounts of drawing, the ways in which drawing - both observed and schematic - can be applied to practical and educational concerns is under re-evaluation. The authors feel this is a most significant area of development, and one which many of the contributors to Thinking through Drawing have been grappling with in many ways.

Superficially, there might be a perceived polarity of approaches: artists are trained in creative enquiry, divergent thinking and intuitive reasoning, while scientists demand rigour and measurability. Artists feel comfortable with ambiguous outcomes and acknowledge the role of the viewer in determining the meaning and content of work, be it written or drawn, while scientists require strict control of variables and seek clearly stated hypotheses and conclusions. Sociologists of science (such as John Law, 2004) draw to our attention that scientists use the former type of reasoning more often than is reflected in their research publications. This raises the issue of our attitudes towards this kind of reasoning. How valid is it? What is its place in research?

One of the central themes of the 2012 symposium is the (mis)perceived polarity between scientific and artistic thinking, how this is reflected in curricula, and how curricula may be developed to better reflect more fluid contemporary attitudes towards disciplinary boundaries. These two types of logic are not the same but, we argue, are complementary and equally valid; furthermore, we argue that both artists and scientists use both analytic logic, and creativity and intuitive judgement in their thinking processes. The Rhode Island ‘STEM to STEAM’ initiative addresses this, as many of the 2012 symposium papers do, by addressing the productive intertwining of generative and analytic modes of thought.

The familiarity artists have with drawing processes puts them in a position to be able to inform scientific enquiry into drawing, and constructive perception more generally. The tacit knowledge and skills they possess afford them the ability to make intuitive judgements about the validity of scientific findings, or the relevance of hypotheses. They may also be well positioned to engage in discourse with scientists, approaching problems from novel and divergent angles.

This gives rise to epistemological issues about the validity of tacit knowledge (or ‘knowledge in practice’ as defined by Schon, 1983). Dual process theory (Sloman 1996, Evans 2003, Kahneman 2003) posits two systems of judgement, what Daniel Kahneman calls “thinking, fast and slow” (2011). This suggests that our implicit knowledge, based on prior experience, unconsciously informs our decision and judgement making, and that this is the basis for expertise and intuitive action. Yet this creates a situation in which accomplished artists and other experts may not be able to fully explain the reasoning behind their judgements. Even so, their judgement may be sound and well informed. How this might be resolved, and how artists may be used as a resource in scientific enquiry, are still matters for debate. A better understanding of unconscious decision-making processes may raise the status of tacit knowledge within scientific paradigms. This is not only relevant to artists who participate in scientific investigations, but also to scientists themselves.

It is clear from many of the examples offered at the symposium, that understandings of perception and cognition reached through scientific enquiry, and those reached through the drawing process, often arrive at the same conclusion, albeit expressed in different terminology. While this is by no means a new argument, the authors feel it is one whose ramifications have not yet fully unfolded.

People use drawing as a means of thinking in many contexts, sometimes without even noticing, and there is room to acknowledge these practices and understand them better. The symposia series aims to bring people together to understand what they get from drawing, how they use it, and how to apply their insights and practices more widely, particularly in education, so that contemporary uses of drawing and visualisation are reflected in our curricula.

**Educational applications/implications**

The expanded understanding of the nature and utility of drawing outlined here needs to be reflected in pedagogy. Attitudes toward learning and teaching may shift and expand through dialogue between disciplines, and between researchers, practitioners and educators.

Art educators have long espoused the value of drawing for visual thinking and analytical learning. David Haley maintains “drawing is integral to perception and cognitive understanding” (2010). This belief is shared between artists, designers, and arts educators, and is visible in much of the literature about drawing education. A growing understanding of the cognitive dimension of drawing activity is pointing to the same conclusion, and producing knowledge and practical outcomes relevant across many educational arenas, in art and design (Riley et al.) and beyond, for example, in the training of surgeons (Wright & Shah 2011) and in the development of mathematical, scientific and literacy skills and knowledge at primary and secondary levels (Kantrowitz 2011, Bobek 2012, Tan, et. al. 2012**).**

The collaborative team of art educators and psychologists Chamberlain, Riley, McManus, Rankin & Brunswick (2011) are combining scientific study of art students with experiential research and insight from artists, students and educators, to explore how observational drawing is learnt and taught. They found associations between drawing ability and academic achievement, visual long-term memory and perception of angular relationships. Having identified these key skills in experienced drawers, they developed a teaching method informed by their findings, which students have reported as improving their observational drawing skills.

Along similar lines Brew (2011) combined knowledge of eye and hand movements from eye tracking experiments and video analysis with experience of teaching and practicing drawing to develop a system for observational drawing instruction. The instruction hinges on the importance of pausing, and strong communication between the hand and eye, rather than the traditional emphasis on ‘learning to look’ as the key to drawing.

In addition to the teaching of drawing skills, drawing as a facilitator of learning in other fields is also on the research agenda. The kinds of thinking associated with ‘creativity’: problem solving, divergent thinking, intuitive judgement making, visualisation and visuo-spatial reasoning are universal skills needed by our future scientists, technologists, engineers and mathematicians, as well as our artists. Particularly as they will likely face unprecedented and diverse challenges their teachers cannot anticipate. Likewise, the kind of analytical reasoning prioritised in STEM education, are also valuable to the artist. Therefore, when we look at this problem from a long-term perspective, we must challenge the disciplinary boundaries of our curricula.

Stephen Farthing offers such a re-definition of the boundaries of drawing as a discipline:

“Peripheral words like: talent, giftedness and perhaps most of all Art tend to get in the way once we start trying to describe what drawing is. […] It doesn’t matter if it is a nineteenth century design for a pavilion or the line in the dirt General Travers asked his followers to cross at Fort Alamo, when I use the word drawing I am thinking of essays, first steps, first attempts and prototypes.” (Farthing 2011: 21)

An artist and art educator, Farthing’s definition of drawing aligns well with what cognitive psychologist Barbara Tversky calls, “tools for thought” (Tversky 2011). In Farthing and Tversky’s views, drawing is not and has never been the sole province of art and design practitioners. The drawing qualifications developed by Farthing with Simon Betts reflect this expanded definition, sidelining issues of skill, or craft, in favour of purpose. As Betts puts it: What I really hope for is that the confidence to draw in whatever method is relevant to the individual student, not weighed down by believing that “good drawing” belongs to one particular group of practitioners, will ultimately allow our students to understand their past and construct their futures. (Betts 2011: 33)

Educational applications are of particular relevance, as education is itself undergoing a paradigm shift. The recent historical emphasis on domain specific knowledge is being replaced by an acknowledgement of the importance of more flexible thinking skills. The ability to identify issues and problems and formulate pertinent questions, to locate relevant information, to ideate, to think divergently and apply these skills in problem solving processes; these are the skills that will be of lasting value to contemporary students, in the current dynamic economic and industrial climate. These skills have historically been at the core of arts education, arguably to a greater extent than in other disciplines. It is with this in mind that the Rhode Island School of Design instigated the STEM to STEAM initiative (2012), that is, to assert the importance of ‘the arts’ among the core disciplines of science, technology engineering and maths.

A more fluid concept of disciplinary boundaries in education is therefore timely, and this is the principle behind the second *Thinking through Drawing* symposium: *Drawing in STEAM,* which aims to facilitate dialogue between these disciplines, in order to reconsider curricula as well as to instigate further cross-fertilisation. The potential of drawing across disciplines in educational contexts is currently being explored by many researchers. In the U.S., federally funded AEMDD projects (Art in Education) Eliza Bobek has found that middle school students absorb chemistry knowledge more effectively when prompted to draw explanations of chemical processes rather than simply write verbal explanations (Bobek 2012). Educational and cognitive psychologists Lynn Goldsmith, Ellen Winner and others are looking at the importance of visualisation for STEM (Science, Technology, Engineering and Math) disciplines, and the ways in which visual arts training may help K-12 students succeed in higher level mathematics and science (Goldsmith et al., 2012).

Ways of thinking that are usually associated with arts education are also valuable outside art and design. There is currently a trend moving towards integration of the arts into STEM disciplines, and this is an exciting area for development as there is still a lot of space for innovation and application of these ideas, and for sharing best practices and rolling out successful initiatives.

**Interdisciplinary research & collaboration**

As our understanding of cognition moves towards a more fluid conception, that accounts for a more networked, integrated model of the mind, body and environment, so our disciplinary boundaries are becoming more fluid, and exchanges of knowledge are taking place across disciplinary and cultural boundaries. Drawing, as a practice that has been an intrinsic part of so many domains beyond art and design for centuries, is well suited as a means to literally ‘draw connections’ across such boundaries. It is the fluidity of drawing, its ‘sketchiness,’ that makes it particularly useful as a vehicle of thought in this expanded context.

Let us propose an analogy here: just as widely dispersed yet coordinated neural connections and networks in our brains and bodies are critical to cognition, research models which reach across disciplinary boundaries are necessary in order to open up new vistas for exploration and discovery. As individuals coming together from different knowledge domains to think through drawing, the symposia feature a number of collaborative teams and interdisciplinary researchers looking at drawing and cognition from a variety of perspectives.

It would come as no surprise to da Vinci that medicine has emerged as an important arena for interdisciplinary collaboration. One of the highlights of the 2011 symposium was artist Jen Wright and surgeon Neil Shah’s presentation on their five year collaboration. They have observed medical practitioners draw routinely, for example, to plan procedures and to explain these procedures to others. Yet, they found that “the variety of methods and uses of drawings has continued to surprise medical staff, who almost always denied using drawing in their work at all.” (Wright & Shah 2011: 109) Wright, by bringing an artist’s perspective into the operating theatre, literally drawing alongside Dr. Shah and others, has shed light on these native drawing practices hidden in plain sight, and in so doing, has helped open up new possibilities for the uses of drawing in training medical students.

Angela Hodgson-Teall drew on her own experience as a medical practitioner in her ‘therapeutic intervention’ *Locating Empathy*, which explored the nature of empathy through an interactive drawing performance. Her intervention used splenic palpation, together with ‘double-blind drawing’ and Shakespearean poetry to “facilitate an altered experience of the act of drawing and communicating” (Hodgson-Teall 2011: 144). The performance raised many issues about relationships and communication in medical situations, which, although not explicitly discussed, were felt in different ways by the participants. Conversely, the performance allowed Hodgson-Teall to re-consider the well-being of patients in regard to her own medical practice from new perspectives. Other works made in collaboration with the NHS trust also use drawing to explore related issues. The 2012 symposium will also include several presentations exploring uses of drawing within medical settings, both as a tool in medical research and as a means by which patients can comprehend their own experiences of illness and treatment.

Other collaborations made use of artists’ implicit knowledge of drawing process. The AIKON robot’s software was developed to replicate visual processes similar to those of human vision, and simultaneously mimic the drawing process of artist Patrick Tresset. In this way, resources were mobilised from the arts, and from cognitive and computer sciences, in an outcome which engaged people’s attention in many ways. While there was a performative element to the robot, it both answered and raised many questions about our understanding of visual processes and how decisions are made and procedures carried out in drawing. Presenting a ‘dis-embodied’ drawer enabled a more implicit engagement with viewers that pointed to questions about the embodied nature of drawing; how the functional constraints of the mind and brain operate in drawing, and what would be involved in a computational re-enactment of this.

These interdisciplinary studies, and others like them, offer examples of how different systems of knowledge and forms of knowing are able to come together to apply research insights as practical outcomes.

Current neuroscience has taught us that our brains are not neatly compartmentalised, as 19th century phrenologists once thought. Widely dispersed neural networks across sensory, motor and executive areas of the brain help us navigate the complex, dynamic and unpredictable environments in which we find ourselves. We use both intuition and logic in tandem to guide us successfully through our daily lives. Aesthetic judgement and scientific rigour are complementary rather than contradictory capacities of mind. A more expansive understanding of the full landscape of human cognition makes room for the role of generative thought in the sciences, and disciplined, analytic thought in the arts. Just as various capacities of thought work best in coordination with one another, so might experts in a variety of fields benefit greatly as they come to talk and work together.

**Unanswered questions**

The research reviewed here outlines the perimeter of a field of study. Outside this perimeter are unanswered questions and future directions for exploration and development. We would like to indicate a few areas we feel are significant; not in the sense of ‘gaps in knowledge’, but of untapped potential and further practical application of theoretical insights and shifting attitudes. In many fields these shifts can be slow to take hold, or else pockets of innovative practice are taking place, creating the need for dissemination and sharing of best practices. In particular, there is a huge potential for teaching practices to be informed by the developments in drawing research outlined above.

* How can artists' tacit understanding of perception and cognition be better drawn on as a resource for scientists studying these phenomena? Can this kind of knowledge gain more credibility or be acknowledged as valid within scientific paradigms as our understanding of it improves? Furthermore, what would it mean for STEM education to embrace these ways of thinking?
* As digital technology for sharing visual imagery as easily as the written word advances, through the internet and current printing processes, how might the uses of drawing, as a means for widespread communication and collaboration, expand?
* How can our pedagogy and curricula evolve to reflect contemporary uses of drawing, and contemporary attitudes to the fluidity of disciplinary boundaries and the value of thinking skills over domain-specific knowledge? What might it look like for graphicacy to be placed on a par with numeracy and literacy? How can drawing ‘as thinking' be better integrated into curricula - and what might be the obstacles? How can teachers and teacher educators be involved in this process? Does it require a radical re-think of existing educational paradigms?
* How can methodological and epistemological issues raised by interdisciplinary models of research, for example arts-science collaborations, be resolved? If artists and scientists speak different languages, how can they speak to each other? Can interdisciplinary research embrace diverse approaches? Can an interdisciplinary enquiry produce a significant contribution to knowledge in more than one discipline? And if so, how might these research outputs be disseminated and received?
* How can we better understand and acknowledge the diverse uses of drawing as a cognitive extension? And how might the untapped potential of these practices be further explored? For example through new technologies?

Drawing is a means to foster thinking across disciplines and collaboration among individuals and creative communities. Much work has yet to be done, to reach out and draw connections between researchers, practitioners, citizens and students who use drawing as a means to think and understand the world in diverse contexts and across knowledge domains both outside and within art and design fields. We’re working towards being able to identify, cultivate and share best practices in the practical uses of drawing. We look forward to seeing how these developments evolve, and hope that by bringing together diverse practitioners and researchers in dialogue, *Thinking through Drawing*, and research activities like it, can help facilitate this process.

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