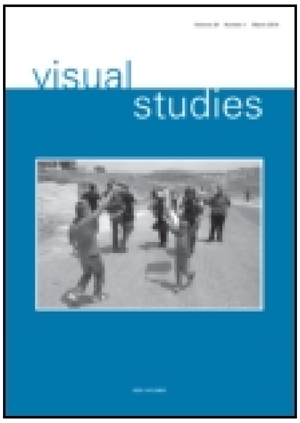

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A pragmatic perspective on visual representation and creative thinking

LEE MARTIN and DANIEL L. SCHWARTZ

This paper offers a cognitive analysis of how visual representations can increase the chances of creativity, while also considering the ways in which they might hinder it. Specifically, it presents four cognitive mechanisms of creativity supported by visualisation: reinterpretation, abstraction, combination and mapping. Each process is described, analysed for potential benefits and pitfalls, and illustrated with examples. Although none of these processes guarantees creativity, together they can increase the odds of a creative moment. The paper concludes with a discussion of how to best prepare people to make use of visuals to support creative thought.

> *It is easier to enhance creativity by changing conditions in the environment than by trying to make people think more creatively.*
> (Csikszentmihalyi 1996, 1)

INTRODUCTION

Creativity is a valued commodity. In business, companies must constantly innovate new products and processes to replace existing sources of revenue. In education, teachers hope to prepare students to go beyond what has come before (Bransford and Schwartz 1999). In art, creativity is the hallmark (Sawyer 2012). Industries that depend on creativity have a keen interest in finding more of it, whether by recruiting more creative individuals, by restructuring institutions to better support creativity (Rogers 2012) or by establishing processes and procedures believed to lead to more creativity (Dow et al. 2010).

Can visualisations encourage creativity and, if so, how and under what conditions? Many answers have been developed on the basis of first-person narratives, field studies, surveys, biographies, analysis of creative works and historical studies of the arts and sciences. In this article, we explore a companion set of answers based on experiments that have tried to increase the components of creativity through the use of visualisation techniques. These studies lend two dimensions to the broader discussion of visualisation and creativity. First, they affirm creative thinking as an important cognitive dimension of both mundane and specialised forms of problem solving. Second, they provide an analytical lens for looking closely at different kinds of visualisations and their implications for the practice of creative thinking.

Creativity and innovation are sometimes characterised as mystical sparks that defy our best efforts at explanation (Johnson-Laird 1989), and early psychological research studied the traits of creative people rather than its causes (Barron and Harrington 1981). More recently, a robust cognitive literature has characterised the processes that support creativity (for representative reviews in psychology, see Csikszentmihalyi 1996; Runco 2004; and Sawyer 2012). For example, in advertising, creative thinking has been so thoroughly modelled that computer programs can match human experts in the creative design of certain classes of advertisements (Goldenberg, Mazursky, and Solomon 1999).

Based on our analysis, we contribute to the contemporary discourse on creativity by offering a modest proposal. Rather than suggesting that people need to think harder or (somehow) more creatively, we explain how deliberate external visualisations can create conditions for creativity – they increase the chances of a creative moment. To make our argument, we offer a cognitive analysis of how visual representations can create opportunities for creativity, whilst also considering the ways in which they might hinder it. Part of our interdisciplinary task is to present the many simple examples and micro-theories from the cognitive literature to help people, who may not be familiar with this discipline, to think about how they might improve their own or others' creativity through visualisation.

We consider four roles that visualisations can play in creativity. They can be organised into a two-dimensional space (Figure 1). The horizontal dimension depicts whether the creative move primarily involves decomposing

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Daniel Schwartz is a Professor at the Stanford University Graduate School of Education. He studies student understanding and representation and the ways that technology can facilitate learning. His work sits at the intersection of cognitive science, computer science and education. A theme throughout Dr. Schwartz's research is how people's facility for spatial thinking can inform and influence processes of learning, instruction, assessment and problem solving.

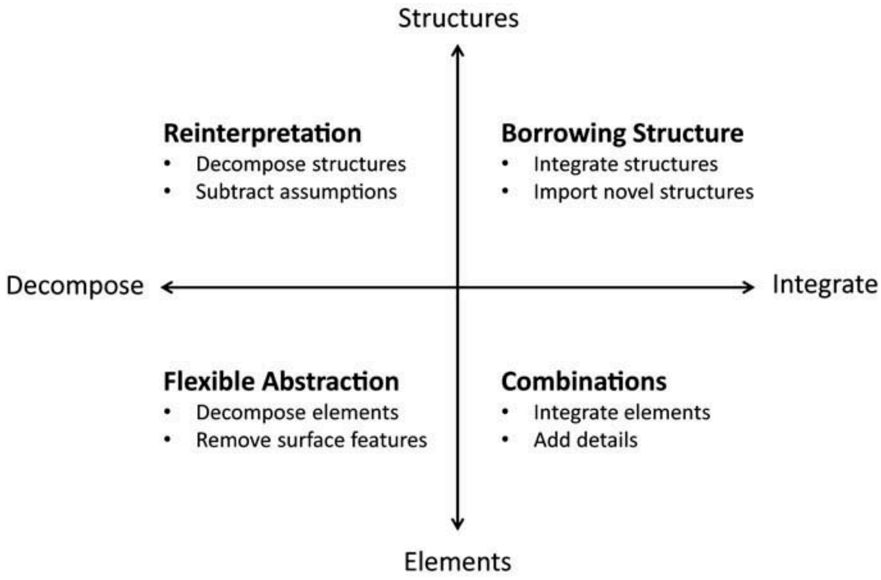

FIGURE 1. Four roles that visualisations play in supporting creativity, arranged in a two-dimensional space.

and subtracting or whether it involves adding and combining. The vertical dimension represents the continuum of focusing on the elements within a visualisation or the structures they create. Of course, people can move throughout the space for any creative act, but the analytic separation helps to specify key moves that enhance creativity through the use of visualisations.

The dimensions make four quadrants that refer to the dominant cognitive mechanisms at play. We present them in outline here, and then in greater detail below. Briefly, they are (a) *reinterpretation*, where visualisations help people to let go of unneeded assumptions and constraints; (b) *flexible abstraction*, where people choose which features of a referent appear in the representation, so that unimportant details can be minimised and important elements can be made salient; (c) *combinations*, where visualisations help people bring together multiple pieces and types of information into one place; and (d) *borrowing structure*, where people take the structures and conventions of one visualisation and apply them to a novel problem.

The visuals we consider are primarily small-scale manipulative materials and drawings, as these are the focus of cognitive psychology research and offer techniques that are within the reach of many. We close the paper by considering ways we might best prepare people to engage in creative visualisation.

VISUALISATIONS AND CREATIVE THOUGHT

To understand the role of visualisation in creativity, it is useful to first examine what creativity entails; not just in the abstract, but also in practice. For our purposes, creativity can be defined as appropriate novelty (cf. Runco and Chand 1995). Novelty captures the sense that an idea is not well worn; it is something new. Appropriateness captures the sense that creative ideas are well suited to a time, context or problem. We need both criteria. Children and the mentally ill can be fantastically divergent and novel, but the unconstrained juxtaposition of ideas is too lenient a criterion for creativity. We are interested in purposeful creativity, rather than random novelty.

Novelty is relative. It can be defined as new to a person, new to a group of people or new to human history. Appropriateness is more difficult to define, as standards change over time and place. Alfred Wegener's creative hypothesis that continents drift over geological time, for example, was rejected by the scientific community at the time. It was only years later that new findings in geology proved his basic hypothesis correct (Jacoby 1981). Nonetheless, within a given time, place and problem-solving context, new ideas can be evaluated for appropriateness. Kepler's brilliant reconceptualisation of planetary orbits into ellipses driven by the sun's mysterious power was certainly appropriate by virtue of explaining known facts and allowing for new predictions, even if it lacked a full explanation of gravity (Gentner et al. 1997).

There is strong evidence that visualisations in the mind's eye can support the generation of appropriate novelty. For example, Finke (1990) experimentally demonstrated that internal mental imagery can lead to appropriate novelty in product design. In one representative task,

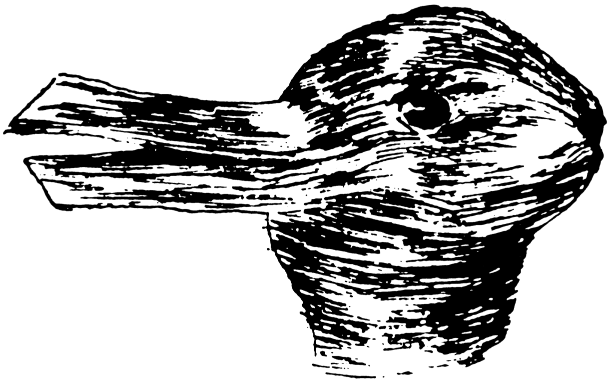

FIGURE 2. Rabbit/duck image used in many psychological studies (retrieved from http://commons.wikimedia.org/wiki/File:Duck-Rabbit_illusion.jpg).

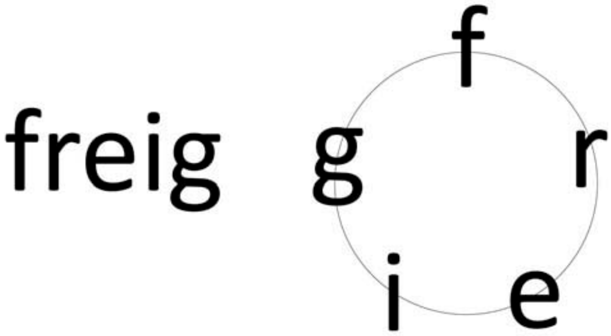

FIGURE 3. Two ways to view letters in an anagram of the word 'grief'. The representation on the left is challenging to solve, as people often verbally rehearse the initial 'fr' consonant cluster. The circular representation on the right is easier to solve, as it allows for both visual and verbal search strategies.

Finke gave participants a set of three simple visual building blocks (e.g. a sphere, a hook and a cone) and told them to mentally combine those elements into an interesting and potentially useful form. Afterwards, he asked them to interpret ways that form might meet a specified need (e.g. a child's toy). Across six 2-minute trials, two-thirds of the participants created at least one invention rated as creative by independent judges.

There are also anecdotal accounts of mental images playing a critical role in scientific discovery (Shepard 1978). Many well-known stories turn on a moment of imagistic insight, such as the story of Kekulé discovering the ring structure of benzene upon dreaming of a snake of atoms biting its own tail (Rocke 1985). Stories of sudden visual insight are compelling, but it is good to remember that beneath the surface of these brilliant moments is an ocean of diligent, careful work. Kekulé, for example, arrived at his dream after years of study and deliberation on the structure of benzene. Indeed, many pairings of visualisations and scientific progress involve slow, deliberate progress, both in the development of the visual form and in its use. For example, the use of Feynman diagrams in theoretical physics evolved over decades, as research teams gradually extended the diagrams' use to novel contexts (Kaiser 2005).

Despite many examples where visualisation and creativity co-occur, there are also times when creativity proceeds without visuals, or where visuals abound but no creative thoughts emerge. Visualisations, then, are neither strictly necessary nor sufficient for creativity. Nevertheless, they can improve one's chances of having a well-structured, creative thought. In the following sections we explain why. While many discussions of creative visualisation focus on the mind's eye and the powers of internal mental images, we take a different approach. We consider how deliberate external visualisations can create conditions for creativity, in part, because they support simple strategies that anyone can execute.

FOUR WAYS EXTERNAL VISUALISATIONS HELP CREATIVE PROCESSES

We will look at four kinds of interactions that visualisations support and consider how the cognitive processes they enlist can facilitate or disrupt creativity. The conclusion we have reached is that the primary positive benefit of external visualisations is that they enable individuals to place representations of their ideas into physical space, where they can be acted upon through both physical and mental actions.

REINTERPRETATION

A critical task in generating a creative idea is letting go of old assumptions that have worked well-enough in the past (Schwartz, Chase, and Bransford 2012). This process can be called reinterpretation or constraint relaxation. Letting go of existing ideas and routines is a canonically difficult task, especially when those ideas and routines have been functioning adequately. A classic example comes from Dunker's (1945) candle problem, which demonstrates *functional fixedness*. Participants in this study received a candle, a small box filled with tacks and a book of matches. Their task was to affix the candle to the wall so that it would not drip onto the table. Few participants thought to use the small box as a candle-holder – they were 'fixated' on the box's usual container function. When given the box separately, with the tacks sitting on a table, the idea of containership was less entrenched, and twice as many participants thought to use the box as a platform for the candle.

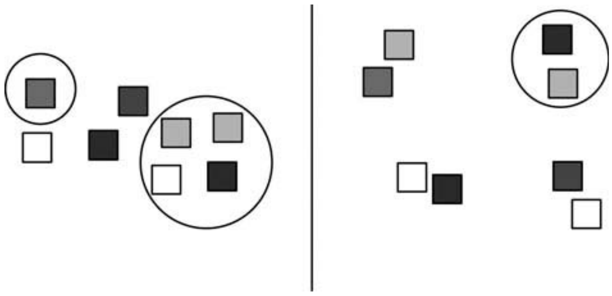

FIGURE 4. Typical student responses to the prompt, 'make one-fourth of eight'. The configuration on the left shows a whole number interpretation, with both one and four tiles circled. The configuration on the right shows a correct interpretation: tiles are arranged into four groups of two, and one group is circled.

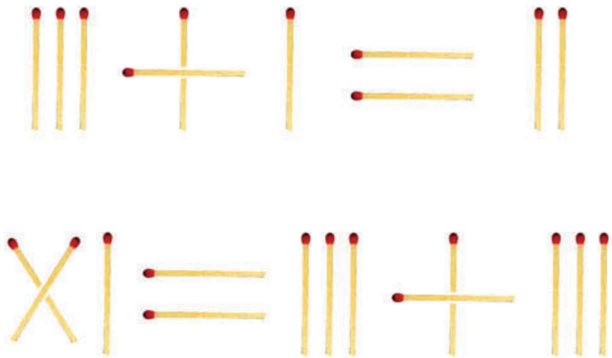

FIGURE 5. Matchstick arithmetic problems, as used in Knoblich et al. (1999). The goal is to make the equation true by moving only one matchstick. Solving the problem on the top involves taking a matchstick from the 'III' and moving it to the 'II'. The problem on the bottom requires one to convert the 'X' into a 'V' by sliding one of the matchsticks.

How might external visual representations aid in the process of letting go of existing ideas and open space for new interpretations? A useful contrast here is between an internal mental image and an external visualisation. To keep a mental image alive, people need to keep refreshing it (Kossyln 1980), and the refreshing process itself will entrench the initial interpretation. As one illustration of this phenomenon, Chambers and Reisberg (1985) had people look briefly at the image in Figure 2, then close their eyes after forming an interpretation of what it represents. When told to search their mental image to see if it could look like anything else, nobody could do so. But having the externalised image at hand provides an opportunity for the reader to move the figure a bit, and eventually recognise a second possible interpretation.

In short, by using an external visualisation, a person can let go of the constant attention required to maintain an internal one. The visualisation is still there, available to be reconsidered with a fresh eye.

These opportunities for reinterpretation can be especially powerful when elements of the visualisation can be moved or rearranged. Maglio et al. (1999) give the example of working with a tray of letter tiles in a word game like scrabble. When people have the chance to physically rearrange letters, they are better able to create words and word fragments. The reason is simple – even random reconfigurations of letters offer the chance of escaping familiar combinations. Given the anagram letters of 'freig' it is hard to find the solution, because the 'fr' traps people. In contrast, the same letters organised as 'grefi' make it much easier to find the solution, 'grief'. A trick for solving anagrams is to arrange the letters in a circle, which helps people to escape the verbal rehearsal of seductive consonant blends (Figure 3).

Martin and Schwartz (2005) demonstrated the benefits of active visual manipulation for children learning about fractions. School children aged 9–11 received problems of the form 'what is ¼ of 8'. At this age, children have a strong natural number schema, so they often interpret the 1 and the 4 as natural numbers rather than a fraction. For example, when asked to circle ¼ of 8 pieces drawn on a sheet of paper, students circled one piece, four pieces, or both. In contrast, when students worked with eight tile pieces that they could move around, they did much better at coming up with the answer 'two' (Figure 4).

When the children had tiles, they began the task by physically moving tiles around. At first their actions were non-systematic but, as they observed the consequences of their actions, they were able to notice groupings that emerged fortuitously. The opportunity to move the tiles invited the formation of groups which in turn helped children to let go of their whole number interpretation of fractions, so that the '1' in ¼ could indicate a single group, rather than a single tile. This set the stage for them to realise that they could make four groups, for which the equivalent of ¼ was one group (of two tiles).

The scrabble and fraction examples highlight the joint processes of generating novelty through interaction with the environment, then evaluating appropriateness of the resulting visual forms. It is important to note, however, that even with external visualisations, people can get locked into the kind of fixed and unproductive interpretations that discourage creativity. For example, Knoblich et al. (1999) studied people solving matchstick problems. Figure 5 provides an example where people had to move a single matchstick so the Roman numeral equation would be true.

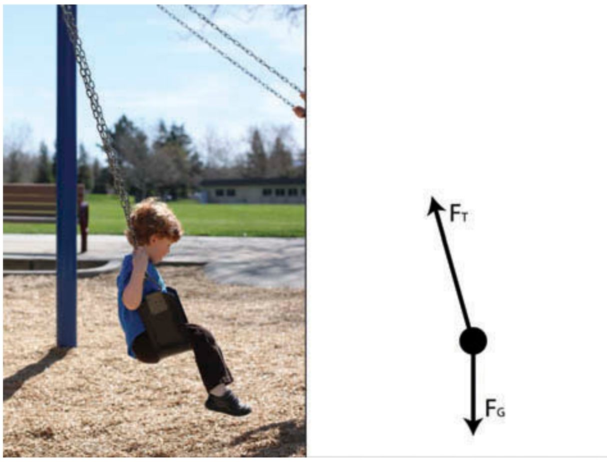

FIGURE 6. Two representations of a child on a swing. The representation on the left is a photograph. It preserves some features of the referent, such as shape and luminosity, while omitting others. The representation on the left is a free body diagram, a common type of representation used in physics. It too preserves some features of the referent, such as position and forces acting on objects, while omitting others.

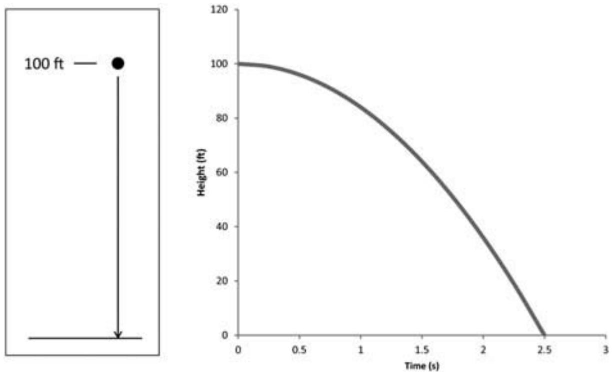

FIGURE 7. Two representations of an object in free fall. The representation on the left shows the object's path through space as it falls in a straight line. The representation on the left is a Cartesian graph of height versus time.

People had trouble with this problem. They could not think of converting the 'XI' into an 'VI' (by sliding one of the vertical lines in the X to make a V, so that 6 = 3 + 3). But why was this so hard? For problems such III + II = II + I, people found it quite easy to borrow a match from the III and add it to the I (i.e. 2 + 2 = 2 + 2). Knoblich et al. (1999) proposed that converting the XI into VI, and other problems like it, are difficult because of the 'tightness' of the element that needs to be decomposed. The three lines in 'III', for example, are not seen as a whole, but rather as three separate adjoined elements, but the two lines in 'X' are seen as a single, non-reducible element. The interpretation of 'X' as an irreducible element overly constrained what people thought was possible.

As this example suggests, the ability to move and manipulate elements of an external visualisation is useful, but it is not a panacea. Not only can people get locked into constraining interpretations, but they can also waste time making unhelpful manipulations. People can fool themselves that they are making progress, because after all, they are doing something. But this may just steal time from more productive avenues. For example, Schoenfeld (1985) has noted that mathematics students often jump into symbol manipulation right away with little or no planning. Their use of algebraic rules to arrange and rearrange symbols looks and feels like mathematical work, but it typically leads the students nowhere, as the algebraic manipulations create only small perturbations in the problem representation and are not likely to lead to novel insights or understandings. Mathematics experts, in contrast, spend substantial time planning, often experimenting with several approaches until they find one that will restructure the problem into a form that is well-understood and solvable.

What then distinguishes cases where producing or manipulating visualisations can support reinterpretation from those cases where it will reinforce a prior interpretation? Two features seem critical. First, the production or manipulation of the visualisation must be at a lower-level than the desired structural outcome. For example, rearranging letters is at the right level of change with respect to finding new words, just as rearranging fraction tiles is at the right level for composing and decomposing groups of differing size and composition. They both allow for the manipulation of atomic components, and they let the visual system detect patterns that emerge. In much the same way, sketching is often a productive problem-solving approach precisely because it allows one to reconfigure relatively low-level elements to see what new structures and relations emerge.

The second trick is to avoid verbalisation or other forms of reification that can fix interpretations too early. Once people lock into a verbal interpretation, it is hard for them to let go and see new structural possibilities (Schwartz and Heiser 2006). One way to avoid the natural tendency to prematurely fix elements by naming them is to create multiple visualisations in parallel. Dow et al. (2010), for instance, had people create product advertisements in serial or parallel. In the serial condition, participants completed an advertisement, received some generic feedback (e.g. 'always think about colour layout'), made a second advertisement for the product, received feedback and so on. All told, the serial participants went through six iterations. The parallel participants made three different advertisements to begin, received generic feedback, made two advertisements, received feedback and then made their

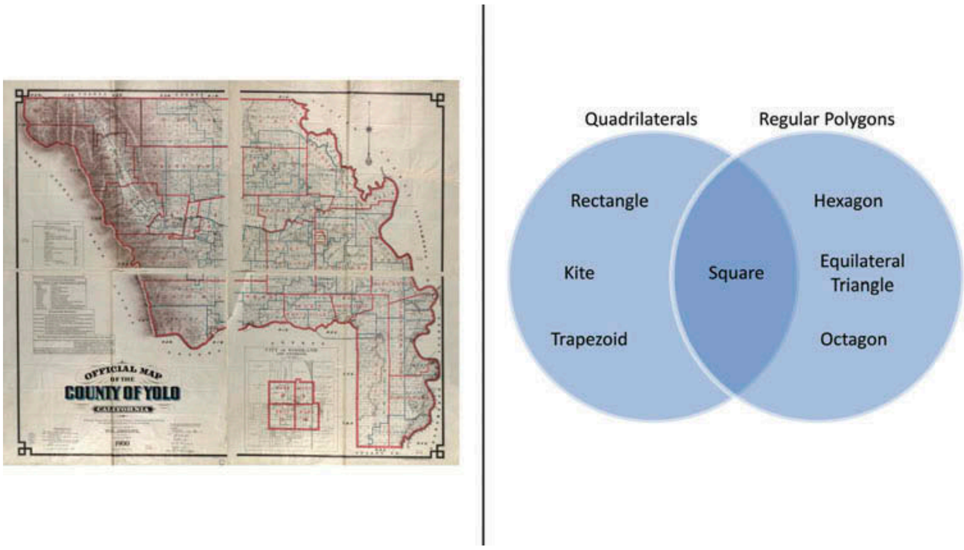

FIGURE 8. Examples of resemblant and co-variant representations. The map on the left is a resemblant representation: it is an abstraction of the landscape, but it contains some elements that look like aspects of the referent, such as the shape of the county's border (Ashley 1900). The Venn diagram on the right is a co-variant representation: it is also an abstraction, but none of the elements in the representation look like features of the referent.

final advertisement. The advertisements of the parallel group were rated higher in creativity by a panel of experts. Moreover, when put on the web, the advertisements of the parallel group led to significantly more 'click-through' where web-users clicked on the advertisement to go to the product's webpage. The serial design process did not work well because participants locked into their first idea, and all the subsequent advertisements were refinements of that idea. In contrast, the parallel participants explored more of the design space before settling into their final idea.

FLEXIBLE ABSTRACTION

The second important quality of visualisations is that they tolerate the omission of details and, as a result, improve the odds of discovering higher-order relations. When we say that visualisations are abstractions of their referents, we mean that they preserve some features, while ignoring others. For example, Figure 6 shows two representations of a child on a swing. One is a photograph, a representation which preserves some features of the referent (e.g. luminosity, shape, perspective), while omitting many others. The second is a *free body diagram*, a common visual representation used in physics for solving problems in mechanics. This representation preserves information about points of contact among objects and the forces acting on them, while omitting information such as shape and colour. The ability to set aside some details can be a boon to creative thinking, especially when the details are both hard to ignore and irrelevant to the problem. As the saying goes, people may not see the forest for the trees. Of course, the creative ideas eventually need to be checked against the details, but it is often better to start at the high-level before zooming in.

Knowing what to include in a visualisation and what to leave out is not trivial. We have often given graduate students the assignment of creating a graph of a simplified dataset from a classic study in psychology. Many students create complicated graphs that include every piece of information in the dataset. While these graphs are visually impressive, they are typically difficult to read and tend to obscure important trends. With time, students learn to experiment with summarising across cases so that trends can be better detected and communicated. As they do so, they are better able to 'see' new patterns in data, a critical skill in the creative work of quantitative and qualitative social sciences.

One challenge of working with visual abstractions is that people can misinterpret the spatial elements. For example, many people interpret north as 'up' or 'higher' when reading maps, and thus falsely conclude that all rivers run from north to south. With even more abstract representations, such as a Cartesian graph, students can impose concrete interpretations that deny the power of abstraction. Consider Figure 7, which shows an object dropped from 100 feet using two different representations. The left shows the path the object takes through space, a straight line from the release point to the ground. The right shows a plot of height versus time. Students can make an iconic interpretation of this plot – they assume that because the plot of an object's motion

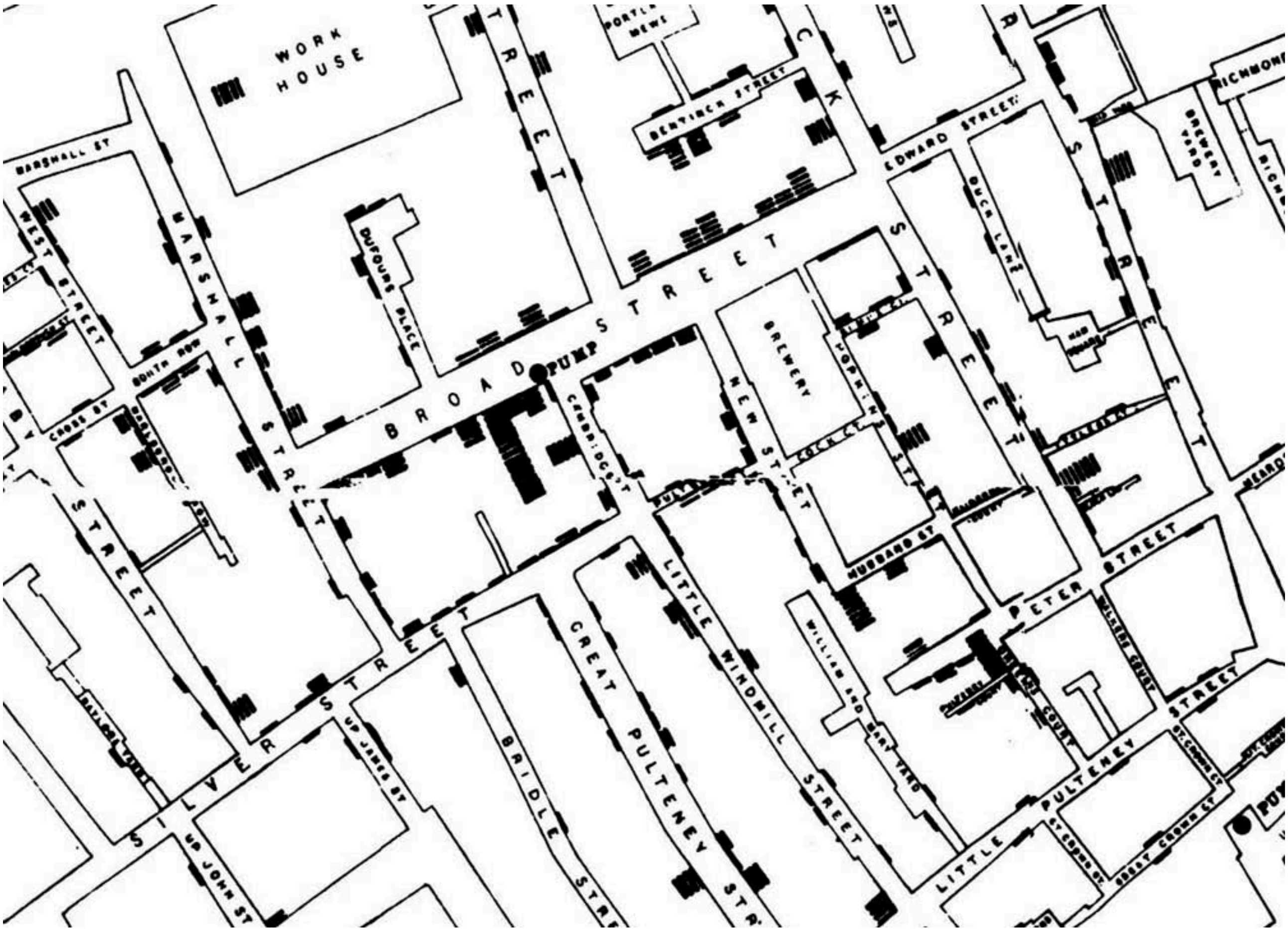

FIGURE 9. A portion of Dr John Snow's map of cases from a cholera outbreak in London in the mid-1800s (retrieved from http://en.wikipedia.org/wiki/File:Snow-cholera-map-1.jpg). The small black rectangles represent individual cases of cholera. The cases are clustered around a water pump on Broad Street.

traces a curve, the object actually moved through a curved path (Leinhardt, Zaslavsky, and Stein 1990). Although the line's curved path is mathematically meaningful (it indicates acceleration), it does not imply curved motion through space. Visual abstractions invite such misinterpretations partly because they rarely are explicit about which features of the referent are maintained and which are omitted.

What is the trick to promoting productive abstraction while avoiding misinterpretation of graphical elements? The solution is somewhat similar to our proposed support for reinterpretation – make multiple abstract visualisations. Here, it is useful to distinguish two types of abstraction: covariant and resemblant (Cummins 1991). Figure 8 shows a map and a Venn diagram as examples of resemblant and co-variant representations. A resemblant visualisation achieves abstraction through subtraction. It removes details, but still looks something like its referent. The map omits many details of the landscape, but it maintains the geometric relations across the map and the landscape it represents. A covariant representation maintains the structural relations of the referent but does not look like its referent. The Venn diagram shows the structural relation of class inclusion, but the overlapping circles of the representation do not look like anything in the referents.

If one's goal is to create new abstract structural relations, our proposal is to make multiple covariant representations because different covariant formalisms are good at revealing different structural relations. A Cartesian graph, for example, is good for showing relations among continuous variables, whereas a Venn diagram is good for showing class inclusion. What does the referent look like when re-visualised as a Venn diagram, as hierarchical tree, as matrix, as a scatter plot and so on? Each covariant representation will highlight different structural relations that permit a new, creative account to emerge. Also, trying out different visualisations increases the chances of catching a misinterpretation driven by a single representation, because people can better detect structural discrepancies by comparing across representations than staying within a single one (Gentner and Colhoun 2010).

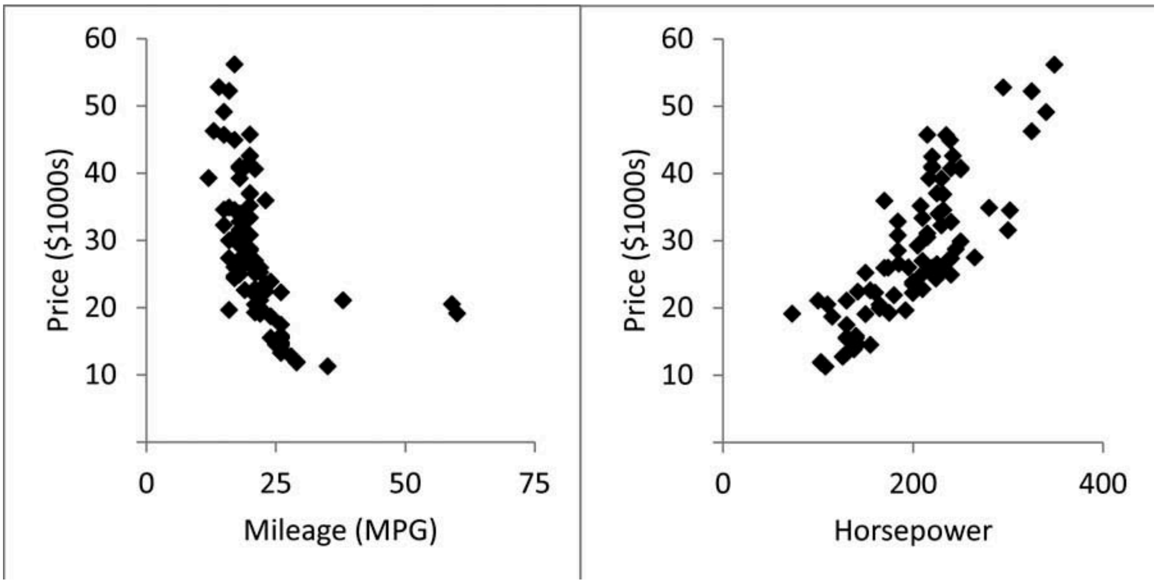

FIGURE 10. The scatter plot on the left shows an apparent negative relationship between miles per gallon (MPG) and retail price. Two hybrid cars are outliers in this graph. The scatter plot on the right shows the positive relation between horsepower and price. Hybrids are no longer outliers in this representation. MPG is not predictive of price after controlling for horsepower. These data represent a sample drawn from the *Journal of Statistics Education* Data Archive (http://www.amstat.org/publications/jse/jse_data_archive.htm).

COMBINATIONS

Letting go of unnecessary constraints and surface features is important for discovering an overlooked structure, but creativity also requires the generation of new structure. Thagard and Stewart (2011) argue that novelty in creativity is often, and perhaps always, the result of combining previously uncombined mental representations. External visual representations can aid creativity by supporting the process of novel combination. Popular brainstorming methods build on this wisdom. Small groups of people, for example, are encouraged to write ideas on a common shared visual field like a whiteboard where they can be arranged and rearranged in physical space so that ideas can be juxtaposed, compared and synthesised.

The ability to combine different types of information from several sources into the same spatial ontology and visual space is a hallmark of many mathematical and scientific representations. The popular story of John Snow's map of a cholera outbreak in London in the mid-1800s offers an example of the power of combining data from disparate sources (Mcleod 2000; Tufte 1983). Snow placed epidemiological data (cholera cases) onto a geographical structure (a map of London), and the resultant map showed a spike in cholera cases near one public water source (Figure 9). Snow's map prefigured work with modern geographical information science (GIS), which combines multiple forms of disparate and otherwise incomparable information (e.g. rainfall, crime rate, income level, air quality) on a single geographic substrate (Edelson, Gordin, and Pea 1999).

The statistical scatter plot is another important example of combinations. The relation between any two quantitatively measured variables can be plotted in a single space, with each dot representing an observation. The scatter plot allows for easy combination of information from two variables, no matter what their source. Once a graph is made, one can readily inspect it for linear and non-linear relationships, outliers and clusters of observations. More sophisticated treatments present several related scatter plots together on one page, allowing for comparison across relationships (Bowen and Roth 2002).

But, as has been the story for other techniques, there are risks with combining disparate types of information into a single visualisation. Scatter plots, for instance, can invite misinterpretation. In our own teaching of statistics, we have found that students examining new car data can readily identify outliers in the scatter plot shown on the left of Figure 10. When these outliers (hybrid cars) are removed, they also readily find the substantial negative correlation between gas mileage and price. This finding leads many students astray, as they invent implausible causal explanations for this trend, suggesting that better gas mileage drives prices down. Although the scatter plot helps students to identify outliers, it can distract them from finding important hidden patterns. In this case, a third variable, horsepower, is a better linear predictor of both retail

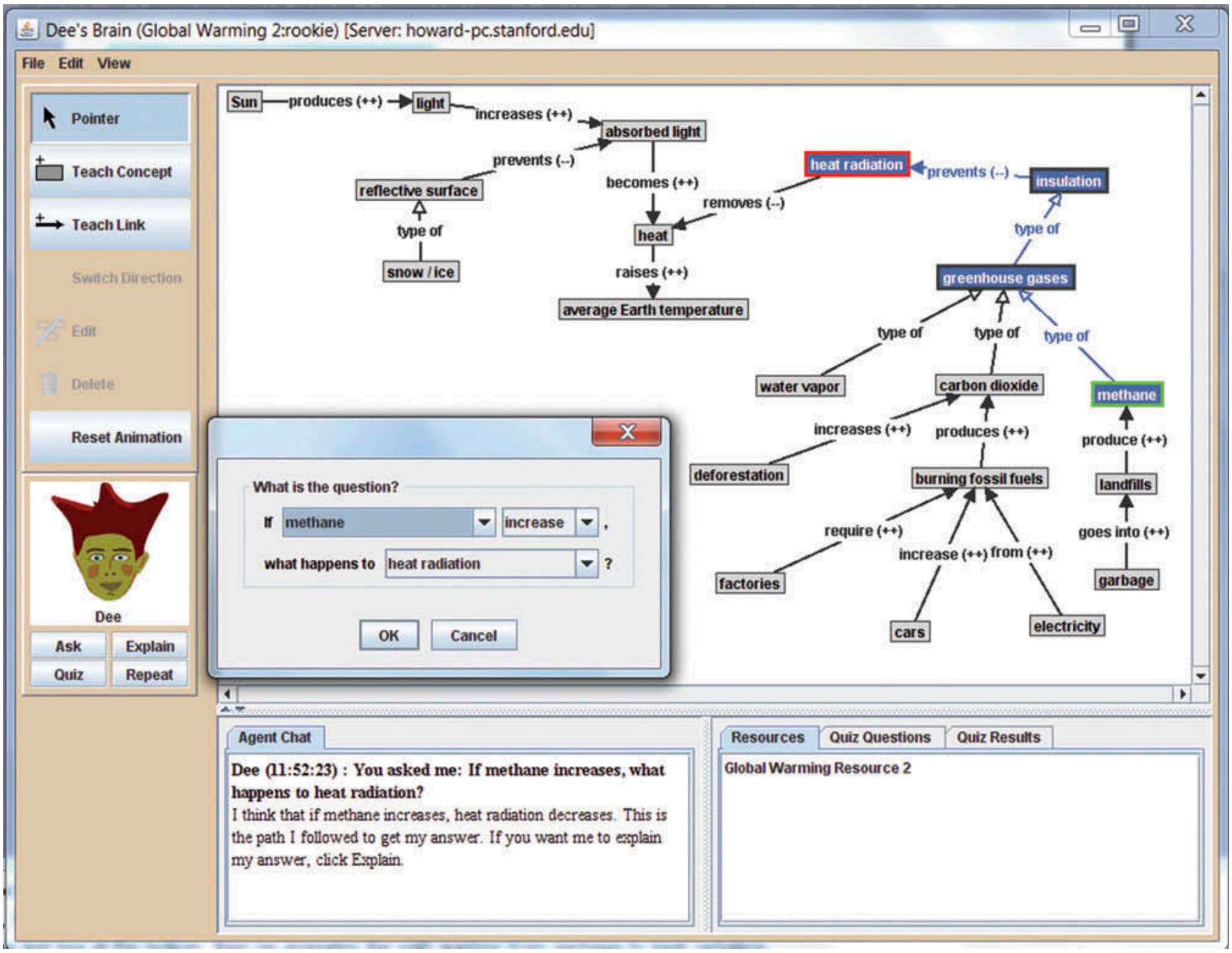

FIGURE 11. A teachable agent that uses visualisation to make causal thinking visible. Children connect the nodes of the agent's brain and indicate the qualitative causal relation. The agent can do causal reasoning based on what it was taught. Here, the agent is following the causal links to reach an answer to the question of 'What happens to heat radiation from the earth if methane increases?'

price and gas mileage (see the plot on the right of Figure 10). When horsepower is accounted for, gas mileage is no longer a predictor of price. Horsepower also offers a more plausible explanation for the data trends – perhaps people pay more for powerful cars, which tend to get worse gas mileage.

This example illustrates that the ease of combining and coordinating does not ensure creative success. People may cling to seductive but spurious results at the expense of continued exploration. Or they may create haphazard combinations that yield interesting but uninterpretable visual patterns.

How can one take advantage of the potential benefits of collecting and coordinating disparate sources of information while avoiding these pitfalls? As before, premature lock-down can be avoided by creating multiple representations. These can involve multiple types of representations, as well as multiple instances of the same type of representation with varying combinations of data. To decide what types of data are good candidates for combination, people must learn to employ some form of filtering, but too strict screening mechanisms will stifle novelty. We hypothesise that the likelihood of creativity can best be enhanced by applying loose criteria initially in deciding which representations to create, and then stricter criteria later in evaluating these representations.

BORROWING STRUCTURE

Reinterpretation, flexible abstraction and combinations are ways in which visuals can help people to let go of old ideas, focus on deep structures and generate novel combinations of ideas. The fourth benefit of visualisations is that they allow people to 'borrow' the structures inherent in the visual formalisms. Visual representations are designed so that meaningful elements of the referent are mapped onto the visual elements in the formalism. Formalisms come bundled with conventions for

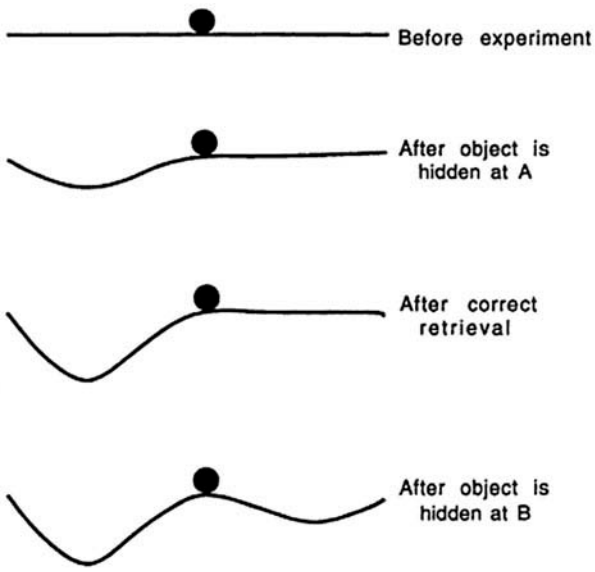

FIGURE 12. A dynamic systems representation of the 'A-not-B error' that 8- to 12-month-old infants make on a hide and retrieve task. The representation shows a ball sitting on a surface. The direction that the ball rolls corresponds to the direction that the child reaches when searching for the object. The ball is inclined to roll towards depressions in the surface on which it sits, and thus the depressions represent attractors towards certain behaviours. Changes in attractors can be represented as changes in the shape of the surface. Thelen, Esther, and Linda B. Smith., *A Dynamic Systems Approach to the Development of Cognition and Action*, figure from page 294, © 1994 Massachusetts. Institute of Technology, by permission of The MIT Press.

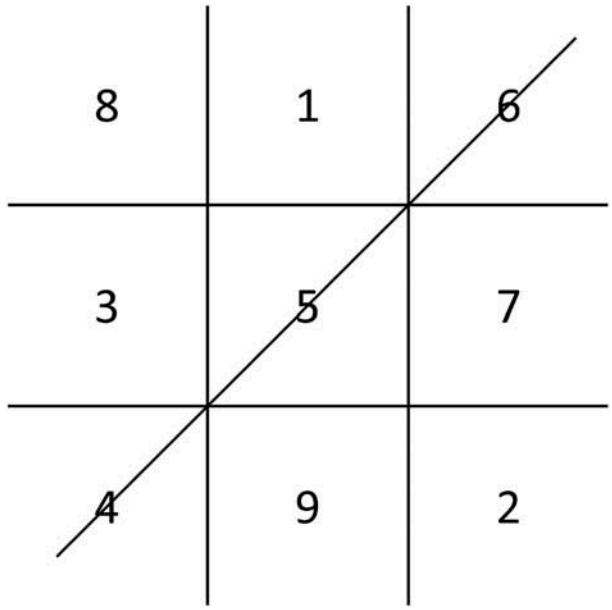

FIGURE 13. A representation of the game of '15' mapped onto the 3 by 3 grid structure of tic-tac-toe. Winning runs in '15' consist of three numbers that sum to 15 (e.g. 4, 5, 6). Winning runs in tic-tac-toe consist of straight lines that connect three cells of the grid.

interpreting visual features like lines, circles, ordering of elements, distance and so forth, and these conventions differ from one representation to another (Collins and Ferguson 1993). For example, when seen on a map, the length of a line can denote geographic distance; when seen on a bar graph, a line means amount. In both cases, the line represents a quantity, but a line can also stand for a boundary, as in the case of Venn diagram. When people adopt a visual formalism, they also adopt its representational conventions.

The benefit for creativity in these processes is that people can procure novel constraints and affordances simply by importing a novel visual representation. This not only offers a path to novelty, it also ensures the resultant outcome will have known structural properties that can be systematically explored and examined for appropriateness. To some extent, the choice of representation also entails a choice of a model for thinking about the representation. As an extreme version of making thinking visible, Figure 11 shows a teachable agent (Chin et al. 2010). Children teach their computer agent (shown in the lower left) by connecting the conceptual nodes that constitute its 'brain'. In this visualisation, each link represents a causal relation (increase or decrease). Using generic artificial intelligence techniques, the agent can answer questions based on what it has been taught. The figure shows how the agent makes its causal reasoning visible as it steps through the nodes to reach an answer. Children learn how to reason causally by adopting the visual representation of the agent.

Why is borrowing a novel representation helpful for creativity? For one, a new representation can carry new opportunities for explanation. Thelen and Smith (1994) wanted to explain a mysterious error that 8- to 12-month-old infants make in reaching for hidden objects (Piaget 1952). In this task, the infants watch as an experimenter hides an object in location A (e.g. beneath a red napkin). Infants of this age can reliably retrieve the object. After several repetitions, they then watch the experimenter hide the object in location B (beneath a blue napkin). Despite having just watched the experimenter hide the object in location B, the infants will reach for location A. This systematic error has been labelled the 'A not B error'. Most attempts to explain this error have relied on theories of infants' developing knowledge of object permanence (i.e. an object does not spontaneously disappear or move). Thelen and Smith instead borrowed the structures and representational techniques of dynamic systems. In this approach, possible behaviours are represented as a changing landscape containing attractors and repellers. Figure 12 shows a simple, one dimensional representation of the A not B error. Here, changes in attraction are shown as changes in a landscape which influence where a ball is likely to roll (or where a child will reach). In this representation, each time the object was hidden in location A, location A became a stronger attractor. Hiding the object at B adds another, weaker attractor. By this account, infants' errors are a result of habit.

One advantage of the visualisation is that it makes it easy to think of predictions. For example, one would predict that infant's behaviour should change as they accrue more experiences that change the depth of the wells on either side of the ball. One would also predict unstable states where infants vacillate between A and B (the wells on either side of the ball are equally deep). Both of these outcomes are true, but had not been explained prior to Thelen and Smith. A good visualisation is a powerful way to generate creative theories.

A more everyday example of borrowing structure comes from the game '15'. In this game, players take turns choosing from the numbers '1' through '9'. The first player whose set of numbers sum to 15 wins. This is a challenging game, and people often make mistakes, such as failing to recognise an opportunity to block their opponent's victory. However, if the numbers '1' through '9' are properly arrayed into a 3 by 3 grid, it becomes identical to the game of tic-tac-toe, and winning runs are easily seen as straight lines (Figure 13). Although '15' and tic-tac-toe are structurally isomorphic, the visual structure of tic-tac-toe is much easier to manage (Zhang 1997).

Reiterating our story of good and bad, a new visual representation can provide novel structures, but it is no guarantee of creativity. For example, when Martin and Schwartz (2009) presented students with a novel medical diagnosis task, some students created and used a matrix or decision tree representation to help them solve it. The structure of the matrix representations mapped well onto the structure of the problem, and these students were able to learn the task quickly and make adaptations as needed. Other students created list-like representations. These representations were also spatially organised and structured, but their structure was not as well-suited to the demands of the task; students who created lists did little better than those who did not create representations of any sort. They managed the task reasonably well at first, but had trouble adapting when conditions changed.

There are two risks when importing a new visualisation. First, the most obviously appropriate representations will likely lead to little innovation. Second, the most novel representations may reflect structures at odds with circumstances of the problem at hand. How can one avoid such pitfalls and increase the chances of choosing an appropriate representation? One solution is to aim for appropriateness at the outset by borrowing representations from domains that share structural similarities. One way to test for structural similarities is by making and evaluating analogies. For example, in the development of the field of cognitive science, researchers made an analogy between the mind and the computer (e.g. both take input, both have memories). It then made sense to borrow representations from computer scientists, such as tree-like data structures, to understand the mind. If no well-structured analogy can be made between two domains, then borrowed visual structures are less likely to be appropriate.

Determining structural similarity in advance of creating representations may help in avoiding inappropriate mappings. But, of course, it may also stifle novelty. As above, we suggest creating multiple representations, drawn from a variety of fields and employing a variety of structures. The ability to generate and evaluate structural analogies between differing domains may help explain the finding that interdisciplinary teams can be particularly creative (Sawyer 2012).This approach has been effective in classroom settings, where students work individually or in small groups to create a variety of structurally distinct representations, then work collectively to find the best elements from the different attempts to create a novel (to them) representation more appropriate to the task at hand (e.g. Danish and Enyedy 2007; Disessa et al. 1991; Enyedy 2005; Lehrer and Schauble 2000; Petrosino, Lehrer, and Schauble 2003).

HOW DO WE PREPARE PEOPLE FOR CREATIVITY?

We have reviewed four pragmatic ways in which external visual representations can enhance people's chances of developing well-structured and appropriate creative ideas. We now turn to a brief discussion of how we might prepare people for creativity. To do so, we must consider people's abilities to manipulate their visual environment in ways that increase their chances of having a creative thought. We believe that this ability can be learned, and we outline three requirements that we believe are essential.

The first requirement is straightforward, pragmatic and unsurprising: to use visual representations, people need to be familiar with them. This *metarepresentational competence* (Disessa and Sherin 2000) includes knowledge of how to create visual representations, how to interpret them and when they are most likely to be appropriate. Without such knowledge, people may struggle both with generating visualisations and with assessing the quality of those that they create or otherwise encounter.

Second, people must have a predilection for creating visualisations. In particular, they must have a level of comfort with the slow and uncertain process of creating representations and exploring the space of possibilities. We see a parallel in Czikszentmihalyi and Getzels' (1970) studies of creativity among painters. They found that art students who forestalled commitment and spent the most time arranging items during a still life painting task not only produced paintings that were judged as more creative at the time, but were more likely to be successful practicing artists many years later (Csikszentmihalyi 1990).

How might comfort with the slow process of creating representations develop? Martin and Schwartz (2009) hypothesise that it develops through extensive practice using representations and seeing their benefits. They found that graduate students who had worked on long-term, independent data analysis projects were much more likely to enlist the benefits of visual representations for solving a novel problem than were undergraduates who did not have those same experiences. In particular, the graduate students were much more willing to incur the significant time cost of creating a visualisation.

Although a predilection for using visual representations may normally emerge over long timescales, it can also be built relatively quickly given the right context. Schwartz (1993) found that, given appropriate instructional experience with visualisations, 12–13-year-old students rapidly learned the value of creating representations to aid them in solving logic problems, and began to do so spontaneously. Not only did they apply the specific visual forms they had learned, they also formed a generalised tendency to create visualisations for novel problems, even when these required visualisations different from those explicitly taught in class.

Finally, we suggest that people should develop preferences for specific kinds of visualisation. For each of the four features of visualisations that we outlined in this paper, we considered strategic choices for maximising the likelihood that the visual would be beneficial to creative thought, and simultaneously minimising the chances of a dead end. Indeed, people will be most likely to enjoy the benefits of visualisation for creativity if they prefer to (and thus tend to) create sets of structurally diverse, covariant representations that bring together information from relevant but disparate sources.

We believe that these three requirements – familiarity, rewarding experiences and specific techniques – can build people's abilities to work with visual representations and increase their chances of having a well-structured creative thought. But we add the following caveat – too strict adherence to any set of requirements is as likely to stifle creativity as it is to foster it. Good designers know when to cleave to design practices, and when to abandon them in favour of trying something new.

CONCLUSION

When analysing human behaviour, it is easy to fall into the trap of one-sided explanations – the analysis fixates either exclusively on environmental factors or on properties of the individual. Because people simultaneously shape and are shaped by their environments, interactional accounts of behaviour often provide better traction on complex issues. In this paper, we described how appropriate visualisation techniques can improve the likelihood of a well-structured creative thought. We used the perspective of cognitive psychology to examine how the properties of visualisations can align or fail to align with thinking and problem circumstances. This approach led us to identify four ways in which visualisations can support creative thought: reinterpretation, flexible abstraction, combinations and borrowing structure.

The analysis we have provided has implications for preparing people to be creative thinkers and problem solvers. While there are many paths that can lead in this direction, our analysis highlights the pragmatic value of learning to master visualisation techniques as an important step towards positively shaping the environment in which people do their thinking. Doing so requires a baseline level of comfort with a suite of visualisations and a preference for visualising when creativity is in demand.

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