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Abstract

Outside the cognitive psychologist's laboratory, problem solving is an activity that takes place in a rich web of interactions involving people and artifacts. Through this interactivity, a reasoner's comprehension of the problem emerges from a coalition of internal and external resources. In the experiment presented here, interactivity was explored under laboratory conditions. Participants were invited to solve an insight problem, the so-called 17 Animals problem. The solution to this problem involves the spatial arrangements of sets. The problem masquerades as an arithmetic problem, which creates a difficult impasse to overcome. Problem solving took place in two different ecosystems: in one, participants were given a stylus and an electronic tablet to sketch out a model of the solution; in a second, participants could interact with artifacts that corresponded to the problem's physical constituent features to build a model of the solution. Participants in the sketch group were never able to break the impasse, that is to abandon their interpretation of the problem as one requiring an arithmetic solution. Participants in the model building group were more likely to break the impasse and discover a productive action trajectory that helped them identify a plausible solution. Video evidence revealed substantial differences in the manner with which participants 'thought' about the problem as a function of the type of interactivity afforded by the two cognitive ecosystems. Insight was enacted through model building activity.

Keywords: Problem solving, insight, distributed cognition, enactivism

Introduction

Problem solving research as traditionally conducted under laboratory conditions is constrained and guided by a number of related methodological and theoretical commitments. Psychologists commonly couch their explanation in terms of mental representation: "representation occurs when a problem solver builds an internal mental representation of a problem" (Mayer, 1995, p. 4). Research focuses on identifying and measuring the processes that modify these representations. An influential perspective on solving so-called insight problems is Ohlsson's (1992) representational change theory (or its more generic activation redistribution variant formulated in Ohlsson's 2011 *Deep learning* book). Insight results from breaking out of an initial impasse, which in turn reflects mental processes—elaboration, re-encoding, constraint relaxation—that transform the representation into one that more clearly anticipates the solution. Since this is a mentalist story, "representational change processes do not correspond to any particular overt behaviors" (Ohlsson, 2011, p. 113).

Fleck and Weisberg (2004; 2013) elaborated a framework to capture the different problem solving strategies triggered when participants repeatedly fail to solve an insight problem. In the early stages, a solution may be proposed through analysis of the problem elements. However a persistent impasse necessitates the restructuring of the problem representation: "insight typically results in solution after a restructuring of the problem, i.e., the solver changes the initial representation of the problem to a new one, in an attempt to develop a new method of solution" (Fleck & Weisberg, 2013, p. 436). Verbal protocols are used as the primary window onto the nature of that representation and the problem solving strategies that are driven by that representation. As the science of problem solving research proceeds on the basis of a mental representation of the world, the world quickly becomes secondary. Under the auspices of this paradigm, the physical presentation of the problem—

its perceptual features and materiality, and the behavioral interactions it affords—remains a peripheral, incidental detail of the experimental procedure.

In Fleck and Weisberg (2013) participants worked through a series of problems. Some of these problems were text descriptions, for example *The Socks* problem read "if you have black socks and brown socks in your drawer, mixed in the ratio 4:5, how many socks will you have to take out to be sure of having a pair of the same color?" (p. 446). Others were descriptions supported by a set of objects that could be manipulated in working toward a solution, for example *The Triangle of Coins* problem: 10 actual coins configure a southern-pointing triangle and participants read "The triangle points to the bottom of the page. How can you move only three coins and make the triangle point to the top of the page" (p. 447). This difference in presentation does not reflect an explicit manipulation of the experimental procedure; in fact it attracts no commentary from the researchers. The resulting difference in problem solving activity is never attributed to a difference in interactivity. Fleck and Weisberg (2013, Table 2, p. 456) report data that indicate that when participants are given artifacts and can interact with a physical presentation of the problem, evidence of restructuring as reflected in the verbal protocols, is much more likely (67%) than when they are not (18%). The authors also propose two types of restructuring, conceptually driven and data driven. The former is guided by analytic mental processes, whereas the latter reflects engagement with the world without intentionality. However the two verbal protocols cited in Fleck and Weisberg (2013)—both from participants interacting with artifacts incidentally—are not sufficiently detailed to permit the isolation and exact segmentation of planning and acting, but in both cases illustrate substantial changes to the physical model of the problem, narrated by the participants (for a more detailed discussion see Vallée-Tourangeau, 2015). Unsurprisingly data-driven restructuring was recorded only with problems presented with manipulable objects (see Table 3, p. 451). These differences attract no reflection or analysis from Fleck and Weisberg.

Cognitive Ecosystems

We would argue that an important, albeit implicit, reason for failing to comment on the role of interactivity in problem solving is the methodological and theoretical commitment to formulating an explanation in terms of mental processes that transform a mental representation of the world. Solving problems, however, outside the cognitive psychologist's laboratory first involves changing the world. That is, problem solutions are reflected in changes in the world; these physical changes are the evidence of a solution. Problem solving in the world involves tools, maps, models—some ready made models as those used in teaching organic chemistry (Toon, 2011), some reflecting constructions using artifacts at hands, like the table top model of a city's landmarks described in Noë (2012)—and unfolds within a set of spatio-temporal coordinates. Solving problems in the world primarily involves action: To solve problems is to act in the word.

The aim of the present experiment was to investigate problem solving enacted within different cognitive ecosystems populated with different artifacts that cued and afforded different actions (Hutchins, 2010). The ecosystem explored in the experiment described below is scaled down to fit laboratory conditions, but cashes in on a fundamental Gibsonian insight that psychology must proceed from a characterization of the organism-environment coupling (Järvilehto, 1998). From the perspective of material engagement theory (Malafouris, 2013), agency and intentionality emerge from interactions with artifacts, and different cognitive ecosystems may well lead reasoners along very different problem solving paths. Participants were filmed as they labored a solution. We chose a difficult problem, a so-called insight problem, which would cue a misleading interpretation. The problem selected was 17 animals, a version of the 27 animals problem described in Metcalfe and Wiebe (1987): how to arrange 17 animals in 4 pens in such a manner that there is an odd number of animals in each pen (a "pure" insight problem according to Weisberg, 1995). This problem masquerades as one involving an arithmetic solution, but can only be solved by overlapping or embedding some of or all of the pens.

Two different ecosystems were created. In the first, participants worked on the solution with a stylus and an electronic tablet. Essentially a traditional pen and paper environment, but with the tablet we could also record the exact sketching and erasing sequences. In the second, a different group of participants worked on the solution by building a model with artifacts (pipe cleaning pieces) to construct pens within which they placed animal figurines. No writing instrument were provided, no sketching or history of prior construction could be consulted.

In the tablet system, people can draw, write, erase symbolic representations such as words and numbers. The system favours a more abstract contemplation of the problem and may perpetuate the arithmetic interpretation of the problem. Since the range of actions is limited, the overlapping insight may rarely be enacted. In addition, a written symbol or a drawn animal enclosure on an electronic tablet cannot be accidentally re-shaped or moved through serendipitous movements. In the 3D system, model building involves playing with props in a game of make believe (cf. Toon, 2011). Without pen and paper, stylus and tablet, participants may be less inclined to simulate moves in the world, to think in abstract terms. Activity is focused on the building of pens from the outset and engagement with the materiality of the stuff—flexible pipe cleaning pieces of various lengths—enacts specific behavior that produces certain shapes and arrangements. Attention is more easily deflected away from an arithmetic contemplation of the problem represented and instantiated by numbers: rather the model is a representative of the world (Noë, 2012) and people directly act in the world. In addition, inexact or hesitant movements coupled with the relative lack of robustness of the material employed can unintentionally transform the world into one that more directly helps the reasoner see a solution. Thus problem restructuring, that is the physical restructuring of the elements that configure the problem, may be more easily enacted in the model building condition.

Method

Participants

Fifty psychology undergraduate and postgraduate students (44 females) received course credits for their participation (M_{age} = 24.2, *SD* = 8.1): Participants were randomly allocated to either the Tablet condition (n = 24) or the 3D model condition (n = 26).

Problem Solving Task

Participants were invited to solve the following problem (the 17 animals problem or 17A henceforth): How do you put 17 animals in four enclosures in such a manner that there is an odd number of animals in each of the four pens? On the basis of pilot work we were confident that this problem encouraged an arithmetic strategy, that is, that participants would aim to solve the problem by dividing 17 into 4 odd-numbered groups of animals. Figure 1 illustrates possible solutions to this problem, which must involve some degree of overlap between sets.

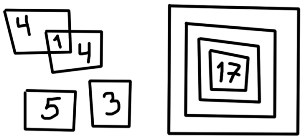

Figure 1: Possible solutions to the 17A problem.

All participants were first presented with a pencil and a blank sheet of paper and given three minutes to sketch possible solutions to the problem. No participant knew the solution to the problem or sketched overlapping pens during that initial period. After an interval of approximately 25 minutes—during which they completed a series of unrelated memory tasks—participants were allocated to either the tablet or the 3D-model condition and were given 10 additional minutes to solve the 17A problem. Participants in both conditions worked on the 17A problem on a table (118cm X 74cm) in an observation laboratory fitted with an overhead camera.

Tablet. In this condition, participants were given a stylus and an electronic tablet (148mm X 197mm) with which to sketch a solution to the 17A problem; participants could draw and erase their workings with the stylus. The participants' sketches were saved as MP4 video clips.

3D Model. In this condition, participants were given approximately 20 pieces of pipe cleaners varying in length (short 20cm and long 30cm pieces) and 17 zebra paper clips (that could also stand on four legs). Participants did not have a pen or piece of paper with which to sketch their solution; rather they had to build a model of the solution.

Table 1: The four features of the numbers, animals and pens dimensions in the tablet and 3D-model conditions. Screenshots taken every 30 seconds were coded for the presence or absence of these features.

	Tablet Condition			**3D Model Condition**	
	NUMBERS			**NUMBERS**	
	Feature	Definition		Feature	Definition
1	Number listed	**Separate N listed outside P**	1	Distinct grouping	**A grouped but not in a P**
2	Number individuated	**Separate N outside P circled, underscored**	2	Marked grouping	**Group of distinct A marked or moved**
3	Number modified	**N struck off or transformed through arithmetic**	3	Group held in hand	**More than one A held in hand**
4	Number change	**New N added**	4	Group change	**New group of A**
	ANIMALS			**ANIMALS**	
1	Animals in pen	**A as countable objects in a P**	1	Animals in pen	**A deliberately placed in a P**
2	Animals listed	**A as countable objects outside a P**	2	Animals listed	**Unrgouped or stray A outside P**
3	Animals individuated	**A as objects marked or moved**	3	Animals individuated	**Single A pointed, touched, held, or moved**
4	Animals change	**Different number of A in P**	4	Animals change	**Different number of A in P**
	PENS			**PENS**	
1	Pens present	**P drawn**	1	Pens present	**P built**
2	Pens shape change	**P shape different**	2	Pens shape change	**P shape different**
3	Pens number	**Number of P different**	3	Pens number	**Number of P different**
4	Pens overlapping	**P overlapping**	4	Pens overlapping	**P overlapping**

Note. Under Definition, **N** = Numbers, **A** = Animals, **P** = Pens

Coding

The participants' problem solving efforts were filmed with an overhead camera. Screenshots from the video data were taken at 30-second intervals and coded along three dimensions to capture the focus of the problem solving activity: (i) numbers; (ii) animals; (iii) pens. The numbers dimension captured the extent to which the screenshot reflected the manipulation of whole numbers (as opposed to treating animals as individuated and countable objects); the animals dimension coded features of the sketch or models where animals were moved and treated as individual objects; the pens dimension coded efforts to draw or build pens of different size, shape, number and spatial arrangement. Each dimension was defined in terms of four features (see Table 1), the presence or absence of which was coded with a 1 or 0, for a maximum score of 4. A 10-minute session was segmented into 20 screenshots; the first and fourth author coded each screenshot independently. The correlations between the coders' average score for each participant along each of the three dimensions in the tablet condition ranged between .838 to .972; for the screenshots in the 3D model condition, these correlations ranged between .860 and .952. There was thus substantial agreement between coders; subsequent discussions resolved the few cases of disagreement.

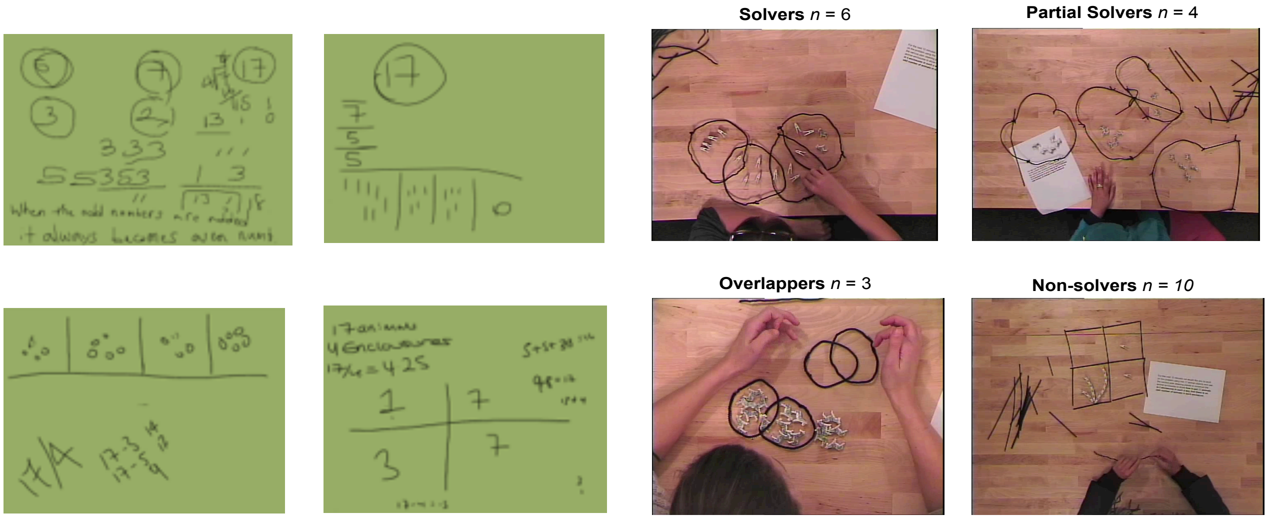

Figure 2: Screen captures using the Procreate app of participants' sketches in the tablet condition (left panels; green background added for contrast); end screenshots of participants' construction in the 3D model condition (right panels).

The agreed coding scores were then averaged across the first 5 minutes of the problem session and across the last 5 minutes to capture whether the focus of the problem solving efforts changed over time.

Results

None of the participants solved the problem during the initial three-minute period. All participants sketched answers that clearly illustrated an interpretation of the problem as requiring an arithmetic solution. After a 25-min interval, participants were given an additional 10 minutes to solve the problem. Of the 24 participants in the tablet condition, none solved the problem in the 10-minute period (see the left half of Fig. 2 for illustrations of the participants' sketching). That is, participants worked for the entire 10-minute period on discovering how an odd number could be split into 4 odd quantities.

Of the 26 participants in the 3D model condition, three systematically clipped the zebras onto the pipe cleaners during the 10-minute problem solving period. This was indeed an affordance of the artifacts employed in this condition, but an unforeseen one when the material was initially piloted. In effect, by clipping the zebras onto the pipe cleaners, these participants could never discover the solution to the problem, since an animal could not be placed into more than one pen simultaneously. This type of problem solving trajectory would not have been possible had we chosen any other type of non-clipping figurines to correspond to the 'animals' in the problems. As a result, we chose to remove these three participants from all subsequent analyses. Of the remaining 23 participants, 6 solved the problem outright (see Fig. 2, right panels) and 4 offered partial solutions—that is solutions with overlapping sets, but ones for which a set intersection is taken as a separate pen, and while there is an odd number of animals in each resulting enclosure, this results in a five-pen solution. Of the 13 who did not solve the problem, 3 worked with overlapping sets but were unable to arrange the animals in a correct manner, and 10 built enclosures that never overlapped. Thus 10 participants provided full or partial solutions to the problem in the 3D model condition, compared to none in the tablet condition, a significant difference, $\chi^2(1, N = 47) = 13.26$, $p < .001$, Cramer's $V = .531$; a more conservative test including only the 6 solvers who provided perfect solutions was also significant, $\chi^2(1, N = 47) = 7.18$, $p = .007$, Cramer's $V = .391$. In both cases, the size of the effect was large.

Focus of Problem Solving Activity

The focus of problem solving activity was measured along three dimensions during the 10-minute video-recorded session: Numbers, animals and pens. At the end of each 30-sec segments, a screenshot of the participants' sketch (in the tablet condition) or the participants' model (in the 3D model condition) was coded in terms of the features of these three dimensions (as defined in the Method section).

We calculated the average mean scores along each of the three dimensions for the first five and the last five minutes of the 10-minute problem-solving period; these are plotted in Figure 3. A few observations: In the tablet condition, participants were more likely to list and modify numbers and change the number of animals in the pens than to sketch different types of pens, and these tendencies were more pronounced in the last 5 minutes of the problem solving session. In fact, for participants who drew pens, once they were drawn, the pens were generally not altered, and remained an invariant presence with which various calculations and animal permutations were attempted. In the 3D model condition, participants were more likely to change the shape and spatial arrangement of the pens and work out how animals fit into those arrangements, than to heap animals in groupings of various sizes outside the pens to determine an arithmetic solution. Unlike in the tablet condition, the level of focus on the animals and pens was high from the start, whereas the focus on manipulating numbers, low in the first half of the session, decreased further in the second half, the reverse pattern to the one observed in the tablet condition. A 3 (dimensions) x 2 (time block) x 2 (groups) mixed analysis of variance (ANOVA) revealed that the main effect of dimension was significant, $F(2, 82) = 13.5$, $p < .001$, $\eta_p^2 = .248$, the main effect of time was significant, $F(1, 41) = 15.4$, $p < .001$, $\eta_p^2 = .272$ but the main effect of group was not, $F < 1$. The more interesting pattern is reflected in the significant dimension by group interaction, $F(2, 82) = 20.2$, $p < .001$, $\eta_p^2 = .330$, which explained the largest amount of variance in the data. This confirms that while numbers was a relatively important dimension in the tablet condition, it was not in the 3D model condition, while the reverse pattern was observed for the pens dimension.

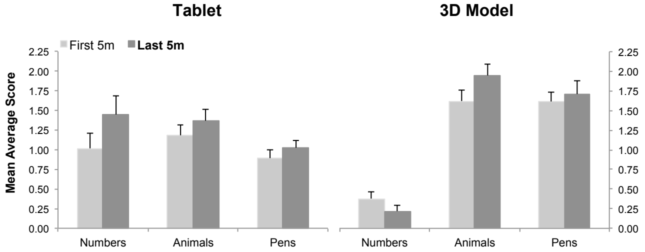

Figure 3: Average mean score for each of the three coding dimensions for the first five and the last five minutes in the tablet condition (left panel) and the 3D model condition (right panel). Error bars are standard errors.

Arithmetic Focus Index. On the basis of the scores on the numbers and pens dimensions, an arithmetic focus index was calculated, for each participant, by taking the sum of the scores on the numbers dimension within a time block and dividing it by the total of the scores on the numbers and pens dimensions. The closer to zero the resulting ratio is, the weaker the focus on numbers relative to pens. Figure 4 plots the arithmetic focus index in the first five and last five minutes in the tablet and 3D model condition. The large group difference is not surprising since participants in the 3D model condition manipulated the objects given to them, namely pipe cleaners and animals, whereas those working with the tablet had a medium with which to list and modify numbers. What is more interesting in these data is the fact that the arithmetic focus index increased in the second half of the problem solving session in the tablet condition, but decreased in that time period in the 3D model condition. This pattern suggests that the arithmetic interpretation of the problem exerted a stronger influence on the participants' thinking in the last five minutes of the session in the tablet condition, whereas it exerted a weaker influence on the participants' problem solving activity in the 3D model condition. A 2 (group) by 2 (time block) mixed ANOVA confirmed these impressions: the main effect of group was significant, $F(1, 41) = 21.3$, $p < .001$, $\eta_p^2 = .342$, the main effect of time was not significant, $F < 1$, but the group by time interaction was significant, $F(1, 41) = 7.20$, $p = .010$, $\eta_p^2 = .149$.

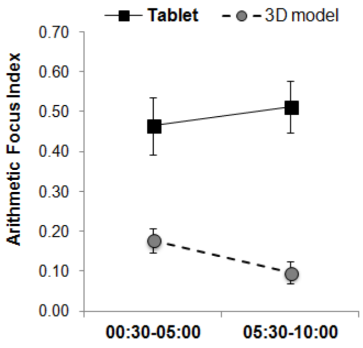

Figure 4: Mean arithmetic focus index in the tablet and 3D model groups for the first and last five minutes of problem solving activity. Error bars are standard errors.

Discussion

The role of interactivity in insight problem solving was explored in different cognitive ecosystems. Participants were invited to solve the 17A problem in a tablet condition—functionally equivalent to pen and paper—or were asked to build a model of the solution by constructing enclosures and manipulating animal tokens, and this without a writing instrument with which to sketch possible solutions. The 17A problem is a difficult problem. Every participant sought an arithmetic solution during an initial three-minute period. Participants subsequently assigned to the tablet condition persevered in their effort to evince an arithmetic solution. The quixotic focus is impressive in light of the rudimentary arithmetic obstacle. Yet, the university students who were assigned to this condition were unable to explore an alternative path to solution. In turn, 44% of the participants constructed models that produced full or partial solutions involving overlapping sets in the 3D model condition. The focus of the problem solving activity differed in the two groups. Participants in the tablet condition worked with numbers and varied the number of animals in four non-overlapping and relatively stable pen configurations. Furthermore, a focus on numbers increased in the last five minutes of the problem solving session. Participants in the 3D model condition built models. From the outset they were much more focused on the shape and arrangement of the pens. The thinking environment in the 3D model condition did not lend itself to the manipulation and transformation of numbers as symbols.

At one level of analysis, participants solved the same problem in both conditions. But the cognitive ecologies were very different. The cognitive ecosystems implemented in the tablet and 3D model conditions were populated with different tools, arrayed in a different physical space, prompted and cued a different range of actions. Participants enacted different hunches and explored different paths to solution in these different ecologies. The problem was more easily restructured when participants engaged in model building activity. The genesis of insight can be understood as an enacted phenomenon produced through the interactivity that couples an agent to the material world: Interactivity is an ontological substrate (Steffensen, 2013). A mentalist perspective focusing on internal processes that restructure a mental representation does not alert researchers to the importance of interactivity and the materiality of the artifacts that populate the ecosystem. While a mentalist perspective may acknowledge the role of the environment in shaping internal representations, the associated ontological and methodological commitments make it difficult to predict how problem-solving performance may differ in environments that support different types of interactivity.

These findings have important implications for the psychology of problem solving. Understanding how people solve problems must proceed from an appreciation of the dynamic coupling between a reasoner and her environment. Fleck and Weisberg (2013) reported but did not comment on the fact that, in their data, restructuring was more likely to occur when participants could manipulate the physical elements of a problem. They probably did not comment on this feature of their findings because they did not assume it would make a difference: If cognition only takes place in the head, it should not. But the problem solving data reported here clearly show that it makes all the difference; the resulting cognitive ecosystem is not a mere implementation detail. How and why people solve a problem reflects a contingent spatio-temporal trajectory (Vallée-Tourangeau & Vallée-Tourangeau, 2014) and different ecosystems may lead to different trajectories: To understand how people solve problems we need to understand how different systems with different properties and affordances may lead to different problem-solving trajectories. More qualitative analyses reflecting a detailed coding of actions and the resulting dynamic configuration of the problem presentation—with its shifting topography of affordances—will likely offer a better explanation of how, why and when someone achieves insight. Methodologically this program of research can only proceed by ensuring that interaction with the physical constituents of a problem presentation is made possible.

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