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Opinion

The future of problem solving research is not complexity, but dynamic uncertainty

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Research on complex problem solving (CPS) has reached a stage where certain standards have been achieved, whereas the future development is quite ambiguous. In this situation, the editors of the Journal of Dynamic Decision Making asked a number of representative authors to share their point of view with respect to seven questions about the relevance of (complex) problem solving as a research area, about the contribution of laboratory-based CPS research to solving real life problems, about the roles of knowledge, strategies, and intuition in CPS, and about the existence of expertise in CPS.

Why should there continue to be problem solving research (in addition to research on memory, decision-making, motivation etc.)?

While it has a long and well established history, particularly the European tradition of complex problem solving (here after CPS) research, its presence in basic science research in cognitive psychology has been somewhat muffled by its stronger role in applied work. Most notably, work on CPS has advanced into applications to educational training, intelligence testing, and a variety of public and private sectors (e.g. automated systems, power plants, air traffic control, flight decks, medicine, data communications network management) (e.g., Kluge, 2014; Müller, & Oehm, 2019; Woods & Hollnagel, 1987). Before we go on to answer the questions posed in this special issue, it is worth looking back to put some historical context to some the issues we consider. Close to 100 years ago in Parker's (1920a, 1920b, 1920c, 1920d) papers, he situates problem solving in the context of educational programmes being implemented in the late 1800's to help students develop the necessary skills to think about a variety of real-world problems that they will face in adult life. Several of the rhetorical questions Parker posed are in the exact same vein as those presented in this special issue 100 years on. Parker's (1920a) states "A problem is a question involving *doubt*" (1920a, pp. 16), and "To maintain the state of *doubt* and to carry on systematic and protracted inquiry-these are the essentials of thinking" (1920d, pp. 258). For us, where the critical connection is between the distant past (Parker, 1920a, 1920d) and recent past (Osman, 2010a, 2010b), as well as the future for research on CPS, is the word "doubt" which is essentially a synonym of "uncertainty". We return to this point at the end of this introduction. The word complex in problem solving research has been an albatross around its neck, as the English expression goes. The burden of trying to agree on what is a complex problem and how to classify problems of different levels of complexity still follows the field around (e.g. Liu & Li, 2012; Quesada, Kintsch, & Gomez, 2005; Schoppek, Kluge, Osman, & Funke, 2018), and there still doesn't appear to be unity on this subject. What seems to be of key interest to communities beyond the study of CPS, is the fact that this research field, like no other, got there first (e.g. Toda, 1962) in trying to characterise the various conditions that we face in the real world when we coordinate a series of thoughts and actions over time to overcome a problem we hadn't anticipated, or a problem for which there is no obvious single solution, or a problem for which there are no clearly defined goals, or a problem which cannot even be precisely defined. The common theme here is that, as Parker had stated, they all present the problem solver with doubt. Actually, we are now at a stage where we can say that that doubt can be more formally described as epistemic uncertainty – a lack of knowledge that the individual has, and aleatoric uncertainty – the inherent noisiness of the conditions (e.g. the weather system) of the problem (e.g., deciding where to direct resources for a future hurricane on the pacific coast). And, just as Parker had asserted 100 years ago, a certain level of epistemic uncertainty is required during the problem solving process, because without it, we wouldn't search for more information to inform how we can better solve the problem. Thus, our position is a fairly strong one, which is that we champion the advances from the field of CPS, but we achieve this by ignoring that it refers to itself as complex, instead we trade complex for uncertainty, actually in particular, dynamic uncertainty, which also happens to be a key feature of Dörner and Funke's (2017) definition of CPS. We also champion the advances from CPS, by anchoring on a psychological process, decision-making under (dynamic) uncertainty, which actually refers to problem solving, and control-based decision-making, and judgement, and learning, and executive memory, etc... We don't begrudge the value of these other mental activities because they are bound to what is needed to solving problems in complex dynamic worlds, but the field needs to move on with the times and engage with the topics that have much more to say about research in the cognitive sciences. For all the sophisticated modelling that goes on (for review see Holt & Osman, 2017) that tells us how to think about formally capturing the phenomena of interest, what the cognitive science community doesn't have, that the CPS community has in ample supply, is a history of expertise

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in devising clever paradigms and innovative measurement tools, and a deep understanding of the psychological intricacies of real world problem solving. One parting thought which is, again, inspired by Parker's (1920a) thinking, is that he understood the importance of the distinction between the value of solving problems individually and where group processes are likely to be important to problem solution. Moreover, he spent time in several of his articles characterising the different types of social contexts in which problems arise. Collaborative decision-making and problem solving is a serious matter of current interest in many research fields (e.g., behavioural economics, macroeconomics, social psychology, decision sciences, data sciences). Here also we would advocate that the field of CPS needs to be embedded in, and engage with researchers from these fields. This is because there is much for this field to contribute and advance our understanding of how groups behave and perform in real world "complex" problems – or as we might more comfortably say, dynamically uncertain decision-making contexts!

We would propose that the cognitive sciences can't operate without dedicated researchers examining how people solve problems, that is a given. There isn't a need to disband the whole field, its value is obviously understood by many, but not by those that should draw from it (e.g., cognitive science/decision science/data science communities). As an illustration, we would say that our recent attempts to bridge computer science with cognitive science, is through the vehicle of CPS – though as we said earlier, we call it dynamic decision-making in (dynamically) uncertain environments (Verduga & Osman, 2019a, 2019b). Why have we done this? Because we know that different disciplines can benefit from the insights made from CPS, and we want to engage with computer science, and cognitive science, and so we have found a way to engage but at the expense of labelling what we do as CPS.

For instance, traditional Artificial Intelligence (AI) approaches to problem solving like the "general problem solver" (Newell et al., 1959), intended to solve well-defined problems, with some limited success. Artificial Intelligence as a field was aware of this when their researchers looked at the work done in the cognitive sciences and found that to capture cognition required understanding how complex problems are solved. The focus initially was on trying to replicate behaviour in well-defined static tasks (propositional logic, chess, math puzzles, etc.). The advances using these tasks took AI only so far. AI found that research done using these microworlds as a test bed for training artificial agents, particularly in decision making, proved useful as a way to outperform humans in specific complex environments (Robertsont & Watson, 2014; Vinyals et al, 2019). As a by-product of continuing the research in problem solving, by having a common playground in which human and artificial agents are acting, such as those developed in the field of CPS, can help enrich psychology and AI, contributing to the design of artificial agents as well as computational modelling of human behaviour (Leibo, 2018).

What are the connections between current CPS research practice and real problems? Where do you see potential for development towards stronger relations?

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Given the artificiality of the laboratory situation, do participants really adopt the presented problems? What insights can be gained despite this artificiality and which cannot?

Yes, there has been work on problem solving in the lab, such as the early work of Dörner's, where participants would spend days solving problems in the lab. Berry's Sugar factory task, while obviously not a realistic task showed us ways of understanding how people make decisions while interacting with a non-linear environment. These paradigms have been instrumental in raising important research questions that have also helped advanced the way we develop measurement tools to examine CPS behaviour. There are also field studies, such as Klein's work notable examples, where problem solving was observed in the wild – naturalistic decision-making. One avenue of work (field study vs. lab study) is no less valid than the other. Both strategies of studying problem solving provided important insights. For instance, in our recent work (Verduga & Osman, 2019a, 2019b), we developed a gaming environment where players were making dynamic decisions in an alien environment where they were interacting with other agents (competitors/threats). Is this an artificial environment? Yes. Is there anything to be gained for this despite it being artificial? Yes, obviously. How is this achieved? This is where theorising and modelling help to constrain the psychological phenomena of interest and allow for careful derivation of hypotheses that can be tested and characterised formally. Moreover, in the study of virtual reality (Millela, 2015; Menelas & Benaoudia, 2017), and more specifically the gamification of CPS scenarios, illustrate how the artificiality of lab based CPS studies are mitigated by demonstrating how they lead to improved experiences of immersion (i.e. believing you are in a real interactive environment). So, we should not have to worry about answering this question by giving up what we have done for the past 60 or more years and only do field research, we are already addressing fundamental basic science and applied questions using paradigms that continue to be of value to many.

What evidence exists for the influence of other kinds of knowledge besides structural knowledge on the results of CPS? Which of these kinds of knowledge should be examined in future research?

Here we would recast the question by talking about what, other than structural knowledge (or perhaps structural representation) - (Schoppek, 2002, 2004), is needed? In other words, what other representations are necessary beyond structural representations (by which we refer to as causal representations) in problem solving? Actually, we would say that causal representations are key (Holt & Osman, 2017; Osman, 2014, 2017) in and of themselves. If the audience is willing to accept our various slights of hand where we exchange "complex" for uncertain, and "problem solving" for decision-making, then there is an amassing body of work that shows that our cognition, at least high order cognition, though may others would argue all of our cognitive faculties, is premised on causal representations that connect our actions with observable effects in the world (or even imagined effects in the world – prospective thinking Osman, 2015). So, it's not necessarily the case that other types of knowledge supersede causal knowledge, what needs to be better understood is how our causal representations evolve with more experience in dynamically uncertain decision-making contexts, and how they can be improved, and how do we construct causal representations in collaborative decision-making contexts, and are they better than those developed individually?

What evidence is available for the impact of strategies (except VOTAT) on the results of CPS? Which of these strategies should be examined more closely?

Again, if the reader is willing to accept our slights of hand where we make exchanges between key terms to discuss decision-making under dynamic uncertainty, then the field invites a whole raft of strategies that have an important bearing, and actually connect with many other disciplines (for review see Mehlhorn et al, 2015; Verduga & Osman, 2019a, 2019b). We are specifically referring to the exploration-exploitation trade-off; searching for new information in order to make a more informed decision vs. utilising the information currently available to make repeated decisions. This trade-off is particularly common in environments of dynamic uncertainty and has practical implications regarding the effective use of resources under time-critical conditions for which the consequences of a sub-optimal decision are high. For instance, many real world problems involve resolving the exploration-exploitation trade-off problem, because accuracy in identifying objects of interest carries the cost of waiting for better and more reliable information, against less accuracy, by making a decision quickly but based on unreliable data. How humans deal with this trade-off is still open to debate, but approaches like the hybrid exploration strategy (Gershman, 2018), combining random and directed exploration (looking for options that provide more information about the environment) could give us insight on the topic and therefore should be the subject of further examination in the context of CPS/dynamic decision-making.

Is there intuitive CPS?

While there is a tradition of research examining the role of implicit or intuitive processes in the field of CPS, there is also work that is highly critical of the methods used to demonstrate that these phenomena are actually critical to problem solving (decision-making), or for that matter, more radically, if they are actually present at all (for review see Osman, 2010). There are many important discoveries that can be made without having to worry about whether the processes are conscious or not, especially given the many current controversies around the theories that have proposed that there are fundamental and dissociated systems/processes which are conscious and unconscious. There is a lot of work that has contested the value of this line of examination, (Melnikoff, & Bargh, 2018; Osman, 2018) in areas outside of problem solving, as well as within the field (e.g., Osman, 2008). If we ask the question: How do we improve CPS (dynamic decision-making)? Then we assume that we can present individuals (and maybe groups) critical knowledge at critical stages to support learning. If we go down the root of discussing intuition, then we get down to having to define what it is, reliably measuring it, and then demonstrating the conditions under which it most likely appears (for some and not others) and how that might present a barrier to improvements in CPS above and beyond other well researched factors (e.g. individual differences, training techniques). In judgment and decision-making, as well as reasoning research, this has yet to be achieved in a way that has not been the source of enormous controversy and now significant challenge. So, the field of CPS, ought to learn from the mistakes of others.

What distinguishes experts in CPS from laypersons?

We actually cannot add any more to the rather pithy and highly insightful point that Parker (1920d) made. He of course was referring to both children and adults when he characterised what constitutes the hallmark of great thinking, which is to raise doubt and use that to inform further inquiry. This doesn't only apply in the context of CPS, it is a property that many have been appealing to, and encouraging more training in to help us all navigate a complex information dense world (Lewandowsky, Mann, Brown, & Friedman, 2016). Without doubt, scepticism, uncertainty, we are too quick to settle on something that requires challenge and to encourage us to learn and improve. We leave the final words to Parker (1920d. pp 258) "The easiest way is to accept any suggestion that seems plausible and thereby bring to an end the condition of mental uneasiness. Reflective thinking is always more or less troublesome, because it involves overcoming the inertia that inclines one to accept suggestions at their face value; it involves willingness to endure a condition of mental unrest."

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