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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 39(0)

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Publication Date
2017

Peer reviewed

Does Associative Memory Play a Role in Solving Physics Problems?

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Abstract

Previous research has found that people frequently provide incorrect predictions about the path of moving objects when given an idealised physics problem to solve. The aim of this research was to explore whether these incorrect predictions are due to the application of an incorrect naïve physics theory, whether incorrect perceptions generated from past experiences lead to misconceptions of how moving objects behave, or whether it is a combination of both. Thirty-one participants volunteered to take part in the experiment which followed a two (experience congruent/incongruent with naïve physics theory) by two (carried versus free-moving object) within-subject design. The dependent variable was participant response (straight down or curved forwards). Results of the study revealed that participants provided answers both consistent and inconsistent with the naïve physics theory. This suggests that responses were primarily elicited through the retrieval of associatively-mediated memories of similar scenarios - some of which contain perceptual illusions. Possible methodological limitations and alternative theoretical explanations are discussed, along with practical and theoretical implications for education and learning.

Introduction

Objects are constantly moving all around us. Therefore, it seems realistic that an individual should be able to correctly predict the path of a moving object (Zago & Lacquaniti, 2005). However, research has found that people are frequently incorrect in their predictions when given an idealised problem to solve (McCloskey, Caramazza & Green, 1980; McCloskey, Washburn & Felch, 1983; McLaren, Wood & McLaren, 2013). The aim of this study is to investigate whether conscious reasoning leads people to apply an incorrect theory to basic physics problems (a propositional account, cf. Mitchell, De Houwer and Lovibond, 2009) or whether automatic associative memories (McLaren, 2011) generate misperceptions of how moving objects behave (the associative account), or even if a combination of both is needed to explain these predictions (a dual-process account (McLaren et al., 2014)). We first introduce the on-going debate as to whether human mental life is best explained in propositional terms, associative terms or both, before going on to consider other related examples of problem solving in humans (and other animals) which may cast light on this research question.

Both the propositional (see also Shanks, 2007) and dual-process (McLaren et al., 2014) approaches agree that human learning incorporates a conscious, calculating component, and that past experiences play a crucial role. However, disagreement exists on whether human learning can be explained by one unitary set of processes or requires multiple processes for its full characterisation. The dual-process approach refers to two modes of processing which are fundamentally distinct: associative processes which create links between representations without conscious knowledge and regardless of the individual's intentions, and cognitive processes which consciously employ rules and reasoning (McLaren, Green & Mackintosh, 1994). It is argued that whilst both human and non-human species are capable of associative learning, humans alone possess rule-based processes which allow logical reasoning (Povinelli, 2004). However, Mitchell, De Houwer and Lovibond (2009) argue that evidence for these two distinct learning processes is ambiguous. They state that rule-based learning and associative learning are part of a combined system where associative learning relies on conscious, effortful and calculated processes, rather than implicit, automatic processes.

The present study explores all three of the theoretical approaches discussed above, in relation to how people solve physics problems. However, the working hypothesis is that associative processes, in the form of associative memory, primarily drive responses to physics problems in most people. Mental rotation tasks share similarities to the basic physics problems used in this current study, in requiring a simulation of the physical world (Neiworth & Rilling, 1987). Therefore, they provide a solid starting point for exploring whether associative memory plays a primary role in responding to these types of problems. During a discrimination task involving shape rotations, Shepard and Metzler (1971) found an increased reaction time for larger rotations. This linear relationship led Shepard and Metzler to conclude that people have a general purpose rotation ability. They suggested that participants created mental representations of the first image and then, when shown the second image, mentally rotated it to match the first. However, something resembling mental rotation has also been demonstrated in pigeons (Neiworth & Rilling, 1987). If humans alone possess rule-based processes which allow logical reasoning (Povinelli, 2004), then mental rotation in pigeons might suggest a role for associative processes in these tasks. Pigeons were trained to respond to images of clocks with rotating hands and were then tested in a discrimination task. Neiworth and Rilling found the pigeons not only performed above chance when discriminating rotations they had been trained on, but also in trials involving rotations they had not been trained on. The pigeons appeared to know where the clock hand should reappear given the time that had gone by, and were able to indicate whether it was right or wrong when the clock hand reappeared. These findings provide support for the primary role of associative memory because the pigeons had considerable experience of successive events during training, and, as a result, were later able to extrapolate novel rotations similar to the rotations they had previously experienced. It can, therefore, be argued that it is also extrapolation based on experience that enables humans to solve similar problems. Rather than utilising a general-purpose rotation ability, people's ability to apparently mentally rotate objects might instead come from their vast experience of objects in different orientations in the environment (Edelman & Bülthoff, 1992). A corollary of this position is that if people's responses are driven by associative memory and experience, then changing contextual variables (i.e. the surface features of the task) should potentially change people's answers. We make use of this logic in the study reported here.

Previous research on naïve physics problems has helped inform the current research. According to McCloskey, Caramazza and Green (1980), when presented with problems involving a ball bearing entering a horizontally positioned curved tube, people tend to utilise the belief that the ball will exit the tube with a "curvy impetus". The majority of participants verbally indicated in a later interview that they believed the ball would acquire a force or momentum in the tube that would cause it to continue to travel in a curved motion upon its exit, gradually losing momentum until the trajectory became straight. This led McCloskey et al. (1980) to conclude that participants were using a naïve theory of motion. McCloskey, Washburn and Felch (1983) later provided evidence for a naïve physics theory in problems involving falling objects. Participants appeared to apply the incorrect non-Newtonian theory that, whilst free-moving objects will fall in a curved motion, carried objects will fall straight down. McCloskey et al. (1983) suggest that a perceptual illusion occurs when people observe a carried object falling. For instance, when an individual drops something whilst cycling, the object ends up behind them due to the cyclist maintaining a constant speed before noticing the object has fallen. Whilst the cyclist continues at a constant speed, the object gradually loses speed as soon as it starts to fall. Although the object falls forward in a curved motion, the observer is likely to believe that the object fell straight down (or backwards) because it is behind the cyclist in their frame of reference.

Whilst it appears that participants are consistently getting basic physics problems wrong due to explicitly applying an incorrect non-Newtonian theory, there is the alternative possibility that these responses are primarily elicited through the retrieval of associatively-mediated memories of similar scenarios - some of which contain perceptual illusions (Zago & Lacquaniti, 2005). Participants may later offer an explanation congruent with a naïve physics theory to justify their reasoning, in an attempt to rationalise their responses in a scientific way. In order to provide evidence for the use of associatively-mediated memories in these problems, it needs to be demonstrated that individuals can produce systematically different answers to essentially the same problem (Sloman, 1996) when the contextual cues accompanying it are varied. If participants cannot explain their answers using a consistent rule, then this indicates automatic associative processing followed by conscious reasoning to justify their initial automatic responses.

A study by McLaren, Wood and McLaren (2013) explored whether experience is primary in explaining why people incorrectly predict the directions of moving objects. Participants were required to complete a questionnaire containing eight physics problems, each concerning falling objects, and were asked to indicate which path they thought each falling object would take. They found that participants gave responses that were both consistent and inconsistent with the naïve physics theory, depending on the context of the problem. In a series of structurally identical but contextually varied scenarios, around half of the carried objects were predicted (on the basis of extrapolation from experience) to fall in a curved forwards motion whilst the others were predicted to fall straight down. Equally, around half of the free-moving objects were predicted to fall straight down whilst the others were predicted to fall in a curved forwards motion. A naïve physics view would predict that all the carried objects fall straight down, and all the free-moving objects follow a curved forwards path. McLaren et al. (2013) argued that if participants' responses were produced by applying a naïve physics theory, the theory would have to be consistently applied across all scenarios. In fact, the variation in contextual cues led to responses that were consistent with their predictions rather than the naïve physics view. Therefore, a more feasible explanation for the responses is that participants were primarily responding to these problems using their own experiences of events similar in structure or context to predict the paths of the falling objects.

The present research was predicated on the existence of both propositional and associative processes in humans. Whilst it might appear that people apply an incorrect naïve physics theory when solving basic physics problems (McCloskey et al., 1980; McCloskey et al., 1983) the presence of the inconsistent responses seen in McLaren et al.'s (2013) study suggests that associative memory plays a significant role in generating these incorrect predictions. Thus, it is possible that participants' responses are based on associative memory rather than propositional inference or reasoning and that naïve physics accounts are later presented as a reason for these responses (i.e. an epiphenomenon). This study aims to extend McLaren et al.'s (2013) work in order to determine whether results in support of the associative account can be replicated under more controlled conditions. In order to do this, a number of possible weaknesses and limitations that were identified in McLaren et al.'s (2013) study were eliminated. Firstly, the number of possible paths of falling objects that participants could pick from was reduced from five to two in order to simplify the analysis of participants' responses. Secondly, the number of problems was increased from eight to twelve to improve reliability. Thirdly, each image was carefully refined to avoid any confounding characteristics such as motion lines and object position – these are now equated across problems. Fourthly, each participant was tested on a computer individually and then interviewed afterwards rather than given a questionnaire to complete in class. This was to strengthen validity of the experiment by avoiding confounding variables such as responses of classmates at the same table and noisy distractions. The interview was done to ensure enough information was provided to generate reliable qualitative data. If these findings show responses that are both consistent and inconsistent with the naïve physics theory, depending on the context in which they are presented, this will support the theory that people are making use of associative memories when responding to these problems.

Experiment

Method

Participants

Thirty-one participants volunteered to take part in the experiment. Participants consisted of 17 females and 14 males (M=26.45 years, SD=8.37) living in Exeter and the surrounding areas (15 undergraduate students, 5 college students, 10 professionals and 1 postgraduate student). All participants had a GCSE in Physics and one had an A Level in Physics. Final year psychology students with prior knowledge of the theories explored in this study were excluded from participation.

Materials and Design

The experiment followed a 2 (experience congruent/ incongruent with naïve physics theory) by 2 (carried/free-moving object) within-subject design. The dependent variable was participant response (straight down/curved forwards). Each participant was presented with the same 12 basic physics problems, constructed using Microsoft Word and Microsoft PowerPoint and programmed using SuperLab software on a Macintosh computer. The experiment contained what was essentially the same physics problem presented in 12 different ways, using different contextual features. All of the problems were framed around falling objects travelling at the same speed. Six problems involved carried objects and the other six problems involved free-moving objects. These two types of problems were divided into subcategories, based on whether the predicted answer was congruent or incongruent with the naïve physics theory. Therefore, the four categories of problems were: Carried – Congruent (e.g. Figure 1), Carried – Incongruent (e.g. Figure 2), Free-moving – Congruent (e.g. Figure 3) and Free-Moving – Incongruent (e.g. Figure 4).

There were three problems in each of the four categories. Carried – Congruent: a seagull in flight dropping an ice-cream, a plane dropping a crate and a running student dropping a book; Carried – Incongruent: a swinging monkey dropping a banana, a plane dropping a bouncing bomb and a running cricketer dropping a ball; Free-Moving – Congruent: a cannonball fired off a cliff, a skier approaching a crevasse and a toy car falling off a table; Free-Moving Incongruent: a river flowing off a cliff, a skater dropping into a half-pipe and a toy train falling off a broken track. The congruent problems were based on problems used in previous research that resulted in responses congruent with the naïve physics theory (i.e. straight down for carried objects and curved forwards for free-moving objects). The incongruent problems, which were designed to elicit responses incongruent with the naive physics theory (i.e. curved forwards for carried objects and straight down for free-moving objects), were selected based on the research team's own visualisations of how the objects would appear to behave from associated experiences (e.g. a skater can be associated with dropping straight down into a half-pipe).

Procedure

Firstly, participants were given a consent form to sign, which briefed them on the procedure of the experiment and their right to withdraw at any time. They then read the onscreen instructions as follows: *"You are about to view a series of scenarios in which objects are seen falling to the ground. Firstly, look at the scenario and decide which path you think the object will take on its journey, and then, from the two choices offered, select which path you think most resembles the one you thought of. Indicate your choice by pressing the corresponding number on the keyboard. For example, if you think Path 1 is most similar to the path you thought of, press the key '1'. When making your choice, please ignore the effects of air/wind resistance and friction. All objects are travelling at the same speed (Speed V). When you have made your choice, let the experimenter know. You will then be asked a couple of brief questions before moving on to the next scenario. Please give as full an answer as possible. If you are happy to continue, press the space bar to begin the experiment."*

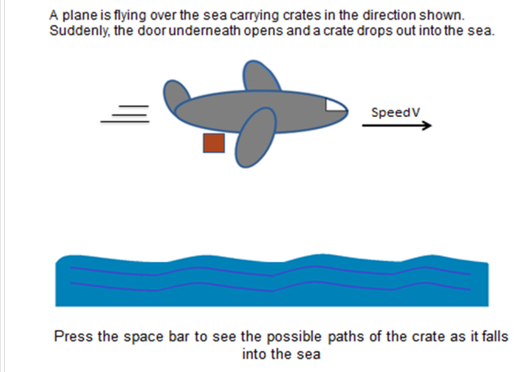

Figure 1. Carried - Congruent Problem

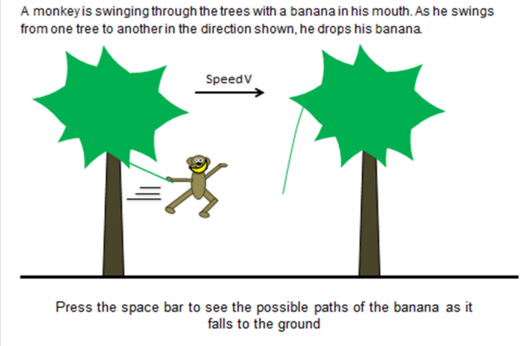

Figure 2. Carried - Incongruent Problem

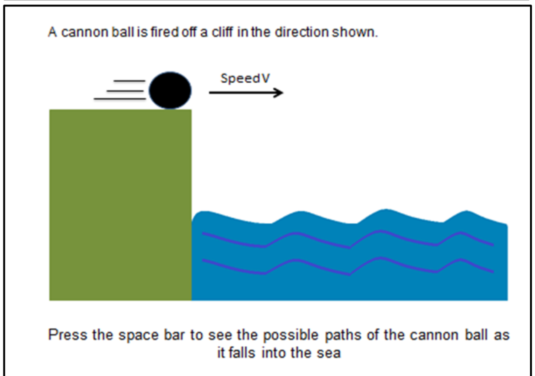

Figure 3. Free-Moving - Congruent Problem

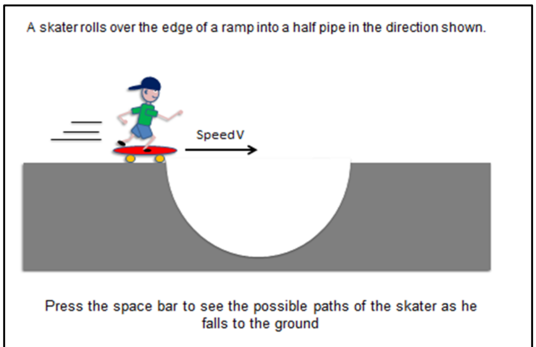

Figure 4. Free-Moving - Incongruent Problem

The experiment began with one of the 12 scenarios appearing on the screen. Participants were provided with information about the scenario (see Figures 1-4) and were then asked to press the space bar to see the possible paths of the falling object (see Figure 5). These were shown side by side, with the object falling straight down or curved forwards. Participants were asked to select the path they thought was most likely. They were then asked to let the experimenter know that they had made their decision. The experimenter responded by asking a set list of questions about the scenario: "What was happening in the scenario?", "Which answer did you select?" and "Why did you select that answer?" The 12 scenarios were presented in random order to prevent bias.

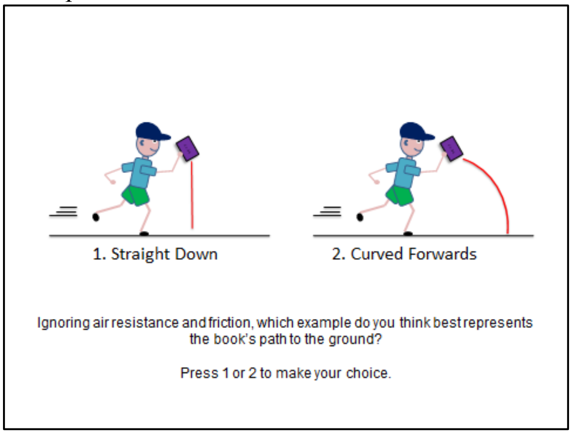

Figure 5. Example of choices provided.

At the end of the experiment, participants were asked if they followed any specific rules to help them complete the experiment and if they had any general comments about the experiment. Participants 13 to 31 were also asked if they felt their approach changed at all during the experiment. This was because it became apparent during the experiment that some participants felt they were trying to apply a rule at first and then they later noticed their responses were inconsistent with the rule they had said they were applying. The experimenter then verbally debriefed participants about the nature of the study. The duration of the experiment was approximately 15 minutes for each participant.

Results

As a first step, the data was analysed using a 4 (condition) x 2 (response) contingency chi-square test to see if the condition (carried-congruent, carried-incongruent, free-congruent or free-incongruent) had a significant effect on the responses given (straight down or curved forwards). A contingency chi-square test was chosen because it investigates whether there is a significant relationship between two variables. A significance level of p = .05 was used for all statistical tests. The results of the analysis, $\chi^2(3) = 66.94$, $p < .001$ suggest that there was a highly significant effect. In other words, the responses given were not independent of the condition. As the condition did appear to have an effect on the responses given (see Table 1), a number of 2 x 2 contingency chi-square analyses were carried out to determine the nature of this effect. Collapsing over carried/free-moving, $\chi^2(1) = 2.43$, $p = .119$ *(ns)* indicates that congruency had no main effect. A similar analysis for carried/free-moving after collapsing over congruency gave a $\chi^2(1) = 3.89$, $p = .049$, which suggests there was a marginally significant relationship between this factor and response. Straight down was the most common response for carried problems and curved forwards was the most popular response for free-moving problems. This finding is consistent with a naïve physics effect.

Table 1
Participants' Responses Categorised by Problem's Condition

Condition	Response	
	Straight Down	Curved Forwards
Carried – Congruent	64	29
Carried – Incongruent	34	59
Free-Moving – Congruent	17	76
Free-Moving – Incongruent	62	31

However, a naïve physics theory predicts a preference for straight down responses for carried objects and curved forwards responses for free-moving objects, regardless of congruency classification. These results were further broken down to investigate whether carried versus free-moving had an effect on response when looking at congruent and incongruent problems independently. The $\chi^2(1) = 48.31$, $p < .001$ for congruent problems and the $\chi^2(1) = 16.89$, $p < .001$ for incongruent problems suggest that carried versus free-moving had a highly significant but quite opposing effect on responses for both congruent and incongruent problems (see Figure 6). It can clearly be seen from Figure 6 that, whilst it is possible to get a pattern of results consistent with a naïve physics theory (congruent problem data shown in blue), it is also possible to construct similar problems that elicit the reverse pattern of results. In the congruent problems, carried objects tended to produce a straight down response and free-moving objects tended to produce a curved forwards response. Conversely, the incongruent problems, revealed the opposite pattern of responses, directly contradicting the naïve physics theory.

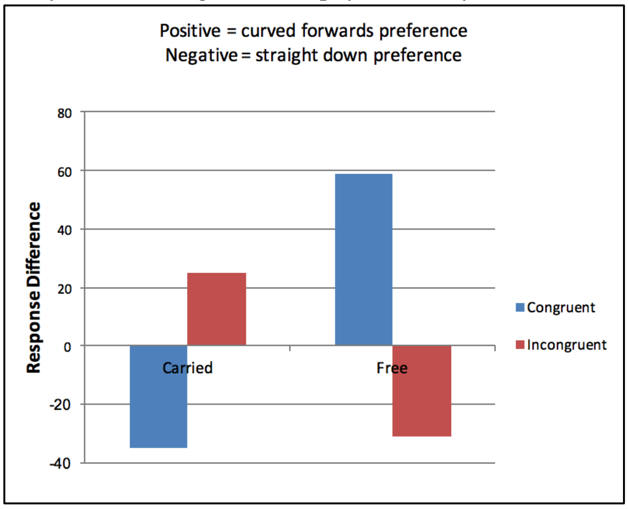

Figure 6. This graph represents the response difference score (No. curved forwards – No. straight down) for each of the four conditions, where a positive score denotes a bias for the curved forwards response over the straight down response.

Discussion

The aim of this study was to determine whether experiences are primary in predicting the answer of basic physics problems. In order to do this, an extension of McLaren et al.'s (2013) study was developed. Specifically, the interest was whether participants responded both consistently and inconsistently with the naïve physics theory depending on the context in which the problems were presented. The hypothesis was that associative processes in the form of associative memory primarily drive responses to physics problems in relatively naïve participants. Therefore, it was predicted that participants would provide answers both consistent and inconsistent with the naïve physics theory based on congruency categorisation. The results of the study revealed that they did.

Evidence for Associative and Cognitive Processes?

Whilst we have strong evidence that contextual variables can influence the responses to essentially the same physics problem, a result which strengthens the case for associative memory influencing these responses, we also have a main effect of carried/free-moving that is consistent with a naïve physics view. Admittedly this effect could be due to the fact that memories of carried objects have a general tendency to elicit a straight down response (and more than a curved forwards response) because of an incorrect perception generated from past experience (McLaren et al., 2013). If the carrier of the object is still moving at a constant speed when the object falls then it will appear that the object has fallen straight down. Nevertheless, this is a post-hoc explanation of this finding, which would have undoubtedly been predicted by a naïve physics account. Thus, we must acknowledge the possibility of a more cognitive component to the responses made to our problems.

When exploring the qualitative data, it becomes clear that many participants do offer something reminiscent of a naïve physics theory when asked to explain their responses. However, the theory provided is inconsistently applied, as congruent questions are predominately explained using a naïve physics theory, whereas incongruent problems are predominately explained by an appeal to experience. If participants were consciously applying different rules in different situations, then they should be able to explain these diverse rules afterwards. However, this was not the case. For instance, in the seagull problem, the majority of participants' explanations were of the form: *"I thought it was most likely to fall straight down or backwards because the bird is in motion but the ice cream is not"*. This sounds like a naïve physics theory, but on the other hand, in the skateboarder problem, the majority of participants' explanations did not refer to theory but to experience: *"If you see skaters on a ramp they usually go straight down"*. Other incongruent problems are explained using an alternative theory. For instance, some participants failed to apply the straight down belief to carried objects but instead attempted to apply the rules of Newtonian physics by simply mentioning gravity: *"gravity will pull it straight down"*. These inconsistent explanations for responses suggest that participants are automatically responding to problems and later coming up with rules when asked to explain why they selected their responses. At the end of the experiment, many participants indicated they had later become aware that the rule they provided as an explanation directly contradicted some of their responses. 74.4% of participants said that they felt their approach to the task changed as the experiment progressed. When asked if they had any further comments about the experiment, 71.0% said "no". However, the remaining 29.0% asked if all the problems had the same answer. This shows that whilst some of the participants suspected that the answers may all be the same due to the similar structure, perceptions based on their own experiences were so powerful that they overrode these suspicions. The fact that the problems used in this experiment were essentially the same basic problem with different surface features shows how vulnerable associatively-mediated retrieval is to a change in the surface features of a problem.

Implications

The findings in this study suggest that when participants are presented with problems, such as the ones in this study, memories are elicited first and rules are inferred later. These findings may have significant implications for education. If experiences are primary to predicting the answer of basic physics problems, this needs to be factored into the teaching methods applied to physics. For instance, children who are studying GCSE Physics are likely to have already formed many memories about the behaviour of moving objects, and because they are likely to believe things that they see with their own eyes rather more than what they are told (Wallach, 1987) this will need to be taken into account. Just telling them the correct theory may not be enough; some explicit acknowledgement of their own experience and why it might be misleading in terms of the physics of the situation may be required.

Strengths and Limitations

This study has successfully replicated McLaren et al.'s (2013) findings using an improved methodology, whereby participants underwent the study in a controlled environment and were able to provide both quantitative data and qualitative data. The results of this study provide strong evidence for the case that associative memory plays an important role in problem solving and learning. However, one limitation of this study is the method of obtaining incongruent problems. The problems which were designed to elicit responses incongruent with the naive physics theory (i.e. curved forwards responses for carried objects and straight down responses for free-moving objects) were selected based solely on the research team's own experience of how the objects appear to behave. It would be useful for future research to find a more independent method of selecting incongruent problems. Another limitation of the study could be that it lacks ecological validity due to the use of images of two-dimensional objects on a computer monitor rather than real-life objects.

It is possible that some propositional theorists may argue that this study does not provide evidence for the primary role of associative memory in problem solving. Mitchell et al. (2009) allow that associative memory may have a role in learning. However, they believe it is propositional reasoning that elicits memories based on previous experience and extracts a rule from them. Therefore, it could be argued that, although the responses appear to be based on the participants' past experiences, it is conscious, propositional reasoning that enables the participants to apply these past experiences to the problems presented in the study. Although this alternative explanation covers most of the facts, it cannot easily explain the pattern of qualitative results found in this study. Participants' inconsistent explanations for their responses suggest that they responded to each problem automatically and later came up with a post-hoc justification to fit the response they had given, even if their justification directly contradicted an explanation they had given for a previous problem. At the end of the experiment, many participants indicated that they had later become aware that their explanations directly contradicted some of their responses. This shows that perceptions based on their own experiences were so powerful that they overrode any logic.

Directions for Future Research

As pointed out earlier, the experiment involves people predicting the path of objects drawn in two-dimensional images on a computer monitor. Although the results of this experiment are highly significant, it is important to find out whether the findings can be generalised to other more practical contexts. A possible extension of this study involves participants predicting the path of falling objects in real-life situations. For instance, a student running with a book along a corridor marked with a tape measure. The student could initially run without dropping the book to give participants a real-life illustration. The experimenter would then explain to the participant that the student will drop the book at a specified point the next time he runs along the corridor and ask them to indicate where they expect the book will fall. This may result in more accurate responses due to greater ecological validity. Alternatively, the scenarios could be presented using a video recording.

This study could be extended by running the experiment with a number of samples of participants from different age groups, academic disciplines, professions, or demographics, in order to determine whether the results can be generalised to different groups of participants. It would also be interesting to run the experiment with children in different developmental stages. Although younger children will have less experience with falling objects, they are likely to rely more on automatic associative memory because, according to Piaget (1972), they will not yet have developed the ability to apply a theory when solving problems. However, interestingly, some research has found evidence for children as young as 5 years old applying what appears to be a naïve physics theory to basic physics problems (Blown & Bryce, 2013; Kaiser, Proffitt & McCloskey, 1985; Vosniadou, 2002). It would be interesting to explore this further.

Another possible direction for future research is to study the transition from associatively-based to rule-based performance when solving basic physics problems. This could be achieved by firstly running the initial experiment with a group of participants to get a set of responses based on associative memory, and then training the same group of participants on Newtonian mechanics before running the experiment (using different problem variants) with them again. In the second trial, the participants would presumably respond correctly to the problems because they would be able to apply a rule they had recently learnt. This may sound straightforward, but note that most of the participants in this study had some knowledge of physics, and still made systematic errors.

Conclusion

In conclusion, this study has provided strong evidence for the primary role of associative memory in human learning and problem solving. The highly reliable results show that people are frequently incorrect in their predictions of the paths of moving objects, highlighting the importance of studying associative processes in humans and their interaction with more cognitive (propositional) processing. We suspect that our results will have practical implications for education, especially instruction in physics and applied mathematics.

References

Blown, E. J., & Bryce, T. G. K. (2013). Thought-experiments about gravity in the history of science and in research into children's thinking. *Science & Education*, *22*(3), 419-481.

Edelman, S., & Bülthoff, H. H. (1992). Orientation dependence in the recognition of familiar and novel views of three-dimensional objects. *Vision Research*, *32*(12), 2385-2400.

Kaiser, M. K., Proffitt, D. R., & McCloskey, M. (1985). The development of beliefs about falling objects. *Perception & Psychophysics*, *38*(6), 533-539.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naïve beliefs about the motion of objects. *Science, 210,* 1139-41.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight down belief and its origin. *Journal of Experimental Psychology: Learning, Memory and Cognition, 9*, 636-649.

McLaren, I. P. L. (2011). APECS: An adaptively parameterised model of associative learning and memory, in Alonso, E., & Mondragón, E. (Eds.). *Computational Neuroscience for Advancing Artificial Intelligence: Models, Methods and Applications*. Hershey, PA: IGI Global.

McLaren, I. P. L., Forrest, C. L. D., McLaren, R. P., Jones, F. W., Aitken, M. R. F., & Mackintosh, N. J. (2014). Associations and propositions: The case for a dual-process account of learning in humans. *Neurobiology of Learning and Memory*, *108,* 185-195.

McLaren, I. P. L., Green, R. E. A. & Mackintosh, N. J. (1994) Animal learning and the implicit/explicit distinction. In: Ellis, N. (Eds.). *Implicit and Explicit Learning of Languages,* London, Academic Press.

McLaren, I. P. L., Wood, K., & McLaren, R. P. (2013) Naïve Physics: the wrong theory? In Knauff, M., Pauen, M., Sebanz, N., & Wachsmuth, I. (Eds.). *Proceedings of the 35th Annual Conference of the Cognitive Science Society*, 1008-1013. Austin, TX: Cognitive Science Society.

Mitchell, C. J., De Houwer, J., & Lovibond, P. F. (2009). The propositional nature of human associative learning. *Behavioural and Brain Sciences*, *32*(2), 183-198.

Neiworth, J. J., & Rilling, M. E. (1987). A method for studying imagery in animals. *Journal of Experimental Psychology: Animal Behaviour Processes*, *13*(3), 203.

Piaget, J. (1972). Intellectual evolution from adolescence to adulthood. *Human Development*, *15*, 1-12.

Povinelli, D. J. (2004). Behind the ape's appearance: Escaping anthropocentrism in the study of other minds. *Daedalus*, *133*, 29-41.

Shanks, D. R. (2007). Associationism and cognition: Human contingency learning at 25. *The Quarterly Journal of Experimental Psychology*, *60*(3), 291-309.

Shepard, R. N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *191*, 701-703.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin, 119,* 3-22.

Vosniadou, S. (2002). On the nature of naïve physics. In *Reconsidering Conceptual Change: Issues in Theory and Practice* (pp. 61-76). Springer Netherlands.

Wallach, H. (1987). Perceiving a stable environment when one moves. *Annual Review of Psychology*, *38*, 1-29.

Zago, M., & Lacquaniti, F. (2005). Cognitive, perceptual and action-oriented representations of falling objects. *Neuropsychologia*, *43*(2), 178-188.