Neuroscience and Biobehavioral Reviews 169 (2025) 105966

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

The computational perspective: A catalyst for research questions in cognitive neuroscience?

Sabrina Trapp[a,*], David Whitney[b,c,d], David Pascucci[e,f,g]

[a] Macromedia University of Applied Sciences, Munich, Germany
[b] Department of Psychology University of California, Berkeley, CA, USA
[c] Helen Wills Neuroscience Institute, University of California, Berkeley, CA, USA
[d] Vision Science Group, University of California, Berkeley, CA, USA
[e] Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[f] The Radiology Department, Lausanne University Hospital and University of Lausanne, Lausanne, Switzerland
[g] The Sense Innovation and Research Center, Lausanne and Sion, Lausanne, Switzerland

ARTICLE INFO

Keywords:
Computational level
Perception
Action
Serial dependence
Hysteresis

ABSTRACT

Where do novel research questions come from? We suggest that identifying key computational problems and comparing solutions across domains can be one source. We exemplify this by looking at perception and action and outline how findings from one domain may generate novel research avenues in the other.

1. Introduction

Research questions are the seeds of the scientific process: they guide years of hard work on data collection and analysis. Throughout the history of science, many significant discoveries have occurred by chance. For example, in 1928, Alexander Fleming discovered penicillin when mold accidentally contaminated his bacterial culture. Similarly, Ivan Pavlov's work on classical conditioning was sparked by an unexpected observation with dogs (Pavlov, 1927), and important findings in neuroscience, like orientation-selective and mirror neurons, were also made accidentally (di Pellegrino et al., 1992; Hubel and Wiesel, 1959). However, relying on these serendipitous moments is not a sustainable research strategy; accordingly, most scientific progress follows a more structured path. Researchers tend to interpret findings through established theories specific to their fields, and become increasingly siloed, bound, and marginalized by the need for a subfield-specific theory to accommodate ever more detailed empirical results. For instance, perception researchers analyze effects based on perception theories, while those studying action use their own frameworks. This compartmentalization can limit innovation and the scope of questions that researchers pursue.

To address this issue, we suggest a new approach that focuses on shared problems across disciplines, rather than sticking to fragmented theories. By prioritizing common challenges, this approach can foster collaboration and innovation in scientific research.

Consider what happens when researchers from different domains – rather than reporting their empirical findings to each other, within the frameworks of highly specific theories – put forth the *major problems* they believe must be solved in their research domains. According to Marr (1982), information processing systems, like the human brain, can be characterized at three levels: first, the level of *implementation*, i.e., how information is implemented by the physical units of the system, such as the neurons; second, the *algorithmic level*, which refers to the representations used for the input and the output of the system and how they are transformed and manipulated in the process; and third, the *computational level*, which describes the goal and the problem that the system has to solve. We argue here that, if one takes such a computational perspective, not only do seemingly different research domains become much more related than they appear at first glance, but this approach can also be a rich source for novel research questions. This approach is not meant to constrain subfields from developing specialized frameworks but to encourage dialogue between disciplines that may initially seem unrelated, focusing on shared computational objectives. In the following, we outline our proposal using the example of

* Corresponding author:.
E-mail address: mailsabrinatrapp@gmail.com (S. Trapp).

https://doi.org/10.1016/j.neubiorev.2024.105966
Received 12 July 2024; Received in revised form 31 October 2024; Accepted 29 November 2024
Available online 30 November 2024

perception and action – two different domains, with tailored questions for each field. When considered from a computational point of view, however, the scope of questions that can be asked could be broadened dramatically. We then extend this approach to additional examples from fields that, at first glance, may seem even more distant from one another.

2. Perception: Many hypotheses

Our perception of things we see, hear, and smell comes naturally and without effort. Yet, the underlying computations are far from trivial. Take vision, for example: external stimuli are initially projected onto the retina as two-dimensional images. However, these two-dimensional patterns of light fail to provide clear insights into the true properties of objects and their relationships in the world. The same retinal image can be generated by objects of varying sizes, orientations, or distances from the eye, leading to the inherent ambiguity of vision — a fundamental challenge. Moreover, the same object can hit our retina from countless different viewpoints, a challenge known as the *invariance problem*, which poses a major conundrum for artificial vision as well (DiCarlo et al., 2012).

Despite years of research and multiple models that perform well on limited data sets, the big question remains: *How* do we determine the identity of a single object — out of at least 10,000 possible objects — within less than 300ms (Hung et al., 2005; Thorpe et al., 1996)?

Essentially, object recognition is a *decision* (DiCarlo et al., 2012), amidst an numerous potential solutions. Take, for example, the image of a spider (Fig. 1), composed of small ovals and lines that could also represent various other objects, such as an ant. Even with relatively simple visual stimuli, arriving at the correct identification is not guaranteed. This uncertainty becomes particularly concerning when the decision at hand, such as recognizing a potentially dangerous spider, has implications for survival.

Similar challenges are faced by the perceptual system at any moment. Yet, we are usually fast and effective at solving them. One way to reduce the many possible interpretations of a visual pattern is to rely on prior experience and the representation of the objects around us that we have formed in the immediate past, as objects tend to maintain coherent behavior over short timescales of seconds (Pascucci et al., 2023). Thus, informing vision with recent past experiences can be intuitively beneficial: if our previous decision was that of a spider, the pattern of black ovals and lines in front of us will likely still be interpreted as a spider, rather than an ant or hairpins (see Fig. 1). In line with this, many studies have reported systematic biases in visual judgments toward the recent history of visual events, even in experimental paradigms where sequences of stimuli are uncorrelated by design. For instance, in tasks involving basic features like visual orientation or motion, observers tend to reproduce the current feature as more like the previous trial than it truly is. Such dependence on the recent past, or *serial dependence* (Fischer and Whitney, 2014; Manassi et al., 2023; Pascucci et al., 2023; Trapp et al., 2021), has been observed across a wide array of stimuli and tasks (Kiyonaga et al., 2017), and may partly reflect the constant recycling of recent events in our visual decisions, so that new perceptual representations do not need to be built from scratch.

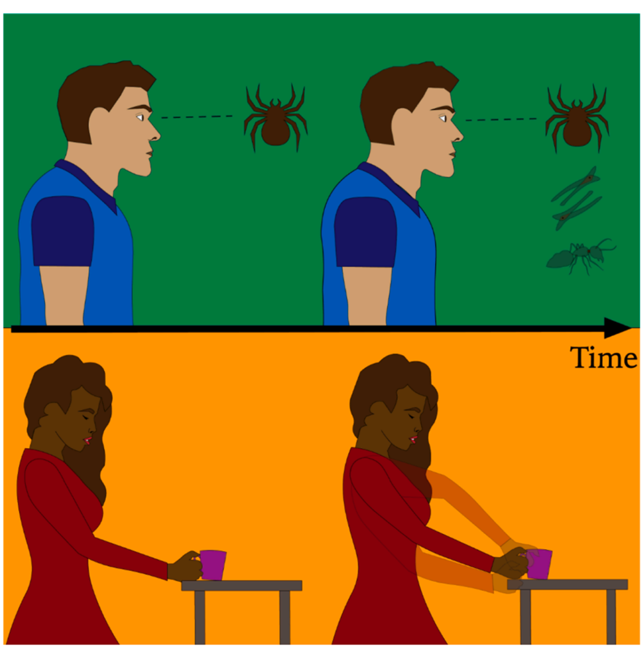

Fig. 1. Commonalities between perception and action. Illustrated is how the past (left side) influences the present (right side) for both perceptual (top) and action decisions (bottom). For both perception and action, there are multiple solutions, and the system has to converge to a fast and robust decision: the sensory input may be compatible with a spider, hairpins, or an ant. For grasping a cup of coffee, the person may use three different trajectories and grasps. The past may be a good proxy for the present when it comes to deciding between different perceptual hypotheses or different action trajectories.

3. Action: Many options

When we navigate through this world, most movements seem to require no effort. Whether grasping a spoon or carrying a glass of wine, our actions are usually executed without any substantial error or delay. However, building robots that can effortlessly move through novel environments still poses a major challenge to artificial intelligence. One reason is that for each movement (e.g., grasping a spoon), multiple postures are possible—a challenge reminiscent of the vision problems discussed earlier. It has been argued that this decision problem is addressed by optimizing a parameter, for example, end-point variance (Harris and Wolpert, 1998). However, is this optimization the only way the brain solves this challenge?

A variety of studies suggest that in some cases at least, the brain adheres to a much simpler strategy: reusing past information. For instance, in a study by Schütz and Schack (2013), participants stood in front of a column of drawers with cylindrical knobs and had to open the drawers either in random or sequential order. To solve this task, participants used a more comfortable pronated grasp for the highest drawers and a supinated grasp for the lower ones. Interestingly, when opening the drawers sequentially, they observed persistence in the previous grasp posture—i.e., a more pronated posture for descending sequences and a more supinated posture for ascending ones. In another study, van der Wel et al., (2007) asked participants to move their hands on a horizontal surface from a circle at the center to a circle at the periphery, and back to the center. When an obstacle was placed between the center and periphery in a previous trial, the hand path in the current trial was significantly more curved, even though a straight trajectory would have been biomechanically more advantageous. Rosenbaum et al. (1992) suggested that previous motor plans are partly re-used, with only a few parameters being computed de novo, thereby reducing the cognitive costs involved in planning new movements.

4. Novel research questions for perception and action

Perception and action share a common challenge: both domains involve multiple hypotheses and competing explanations, and there is a need for these to converge into a coherent solution. A promising avenue of research could emerge by considering questions traditionally asked in the context of perception within the domain of action, and vice versa. This cross-pollination of ideas could provide fresh insights and lead to new hypotheses that integrate both fields. Serial dependence serves as a prime example, suggesting that both perception and action can benefit from leveraging past experiences as templates to address their respective challenges. If perception and action share common computational goals, could we then explore questions and empirical findings from the perception domain and consider whether similar patterns or mechanisms might exist in action? Conversely, can insights from action reveal new directions for understanding perception? By drawing parallels between these domains, we might uncover cross-disciplinary insights that lead to novel research questions and hypotheses.

Serial dependence in visual decisions often involves specific stimulus features, such as orientation or motion, regardless of other properties of an object (Ceylan et al., 2021; Tanrikulu et al., 2023). This may stem from the nature of visual tasks, where observers focus on reproducing specific features independently of others (Houborg et al., 2023). Translated to the domain of action, a key question is whether serial dependence operates more prominently on multiple integrated features for objects requiring specific actions, such as grasping or pushing. Similarly, another intriguing question is whether the magnitude of serial dependence varies depending on whether a stimulus demands a verbal or motor response.

Moreover, serial dependence occurs even when the previous stimulus falls on relatively distant retinal locations (Fischer and Whitney, 2014). While there is no direct analog to the retina in the action domain, it would be interesting to investigate how the position of a visual stimulus relative to the body and the type of action required modulate serial dependence. Similar questions arise regarding the time scales of these phenomena: Does the time scale of serial dependence vary with the speed of the required actions?

Another approach could involve investigating the influence of spatial and semantic contexts on serial dependence in both action and perception. For instance, consider how the context of a bathroom might lead one to expect a hairdryer rather than a gun, thereby narrowing down the decision space to more likely hypotheses (Trapp and Bar, 2015). Similarly, one might explore whether decisions about a particular movement trajectory are influenced by spatial or semantic context—for example, whether certain postures are more readily adopted in specific scenarios, such as within a porthole versus a living room at home.

In sum, these examples demonstrate how cross-disciplinary bridges between perception and action can generate novel research questions. Similar principles may extend across a broader spectrum of disciplines. This integrative approach could, for instance, involve merging insights from engineering, optimal control theory, and vision science to address ill-posed problems (Poggio and Torre, 1984), integrating classical learning models with contemporary attention theories (Turatto, and Pascucci, 2016; Turatto et al., 2018), applying fluid dynamics to model brain activity patterns (Deco and Kringelbach, 2020), or using semantic frameworks to decode neural content (Doerig et al., 2022).

5. Outlook and summary

Formulating research questions by integrating common computational goals from various fields is a valuable exercise, as demonstrated by the examples provided here. Ignoring these shared goals could limit studies in perception and/or action by confining them to domain-specific paradigms and theories, thereby overlooking how the brain implements strategies to solve complex problems across different processing domains. While we have illustrated this concept through examples in perception and action, integrating knowledge from diverse fields is a strategy applicable across many domains. Ultimately, this approach is an effective way to develop overarching theories and generalizable models that transcend narrow subfield boundaries.

Traditional cognitive science and neuroscience often operate at the algorithmic or implementation level, focusing on which neurons, brain structures, or mechanisms are involved. However, the fundamental question of why certain cognitive faculties possess specific features—and what problem they are trying to solve—remains rather underexplored. While addressing this question directly may not always be feasible, emphasizing it can be immensely beneficial for advancing our understanding. For example, asking what problem a limited short-term memory may be solving can reveal new perspectives and guide future research (Trapp et al., 2021). In this paper, we argue that keeping sight of these "why" questions is essential for pushing the boundaries of cognitive neuroscience, even if the answers are not immediately apparent.

Through this work, our aim is to encourage the perspective of viewing at the narrower problems within each research field from a broader, more integrative and computational viewpoint. We propose that this approach is one of several ways to generate new research questions. It is not the only approach; many classical perspectives in the philosophy of science offer valuable insights. Furthermore, current methodologies that focus on specialized sub-theories are certainly valid and have contributed significantly to our understanding of various fields. However, we propose an additional strategy that aimed at enriching the questions being asked. By promoting interdisciplinary collaboration and addressing common issues across domains, we hope to broaden the scope of inquiry and foster innovative insights that may not emerge within narrower frameworks.

Acknowledgments

We thank David Rosenbaum for comments on preliminary draft of this manuscript and Cristina Ghirardo for the figure art. The contribution of DP to this work was supported by the Swiss National Science Foundation (grant numbers PZ00P1_179988, PZ00P1_179988/2, and TMSGI1_218247).

References

Ceylan, G., Herzog, M.H., Pascucci, D., 2021. Serial dependence does not originate from low-level visual processing. Cognition 212, 104709. https://doi.org/10.1016/j.cognition.2021.104709.

Deco, G., Kringelbach, M.L., 2020. Turbulent-like dynamics in the human brain. Cell Rep. 33 (10).

van der Wel, R.P., Fleckenstein, R.M., Jax, S.A., Rosenbaum, D.A., 2007. Hand path priming in manual obstacle avoidance: evidence for abstract spatiotemporal forms in human motor control. J. Exp. Psychol. Hum. Percept. Perform. 33 (5), 1117–1126. https://doi.org/10.1037/0096-1523.33.5.1117.

DiCarlo, J.J., Zoccolan, D., Rust, N.C., 2012. How does the brain solve visual object recognition? Neuron 73 (3), 415–434. https://doi.org/10.1016/j.neuron.2012.01.010.

Doerig, A., Kietzmann, T.C., Allen, E., Wu, Y., Naselaris, T., Kay, K., & Charest, I. (2022). Visual representations in the human brain are aligned with large language models. *arXiv preprint* arXiv:2209.11737.

Fischer, J., Whitney, D., 2014. Serial dependence in visual perception. Nat. Neurosci. 17 (5), 738–743. https://doi.org/10.1038/nn.3689.

Harris, C.M., Wolpert, D.M., 1998. Signal-dependent noise determines motor planning. Nature 394 (6695), 780–784. https://doi.org/10.1038/29528.

Houborg, C., Kristjánsson, Á., Tanrikulu, Ö.D., Pascucci, D., 2023. The role of secondary features in serial dependence. J. Vis. 23 (5), 21. https://doi.org/10.1167/jov.23.5.21.

Hubel, D.H., Wiesel, T.N., 1959. Receptive fields of single neurones in the cat's striate cortex. J. Physiol. 148 (3), 574–591. https://doi.org/10.1113/jphysiol.1959.sp006308.

Hung, C.P., Kreiman, G., Poggio, T., DiCarlo, J.J., 2005. Fast readout of object identity from macaque inferior temporal cortex. Science 310, 863–866. https://doi.org/10.1126/science.1117593.

Kiyonaga, A., Scimeca, J.M., Bliss, D.P., Whitney, D., 2017. Serial dependence across perception, attention, and memory. Trends Cogn. Sci.

Manassi, M., Murai, Y., Whitney, D., 2023. Serial dependence in visual perception: a meta-analysis and review. J. Vis. 23 (8), 18. https://doi.org/10.1167/jov.23.8.18.

Marr, D., 1982. Vision: A Computational Investigation Into the Human Representation and Processing of Visual Information. W. H. Freeman, San Francisco.

Pascucci, D., Tanrikulu, Ö.D., Ozkirli, A., Houborg, C., Ceylan, G., Zerr, P., Rafiei, M., Kristjánsson, Á., 2023. Serial dependence in visual perception: a review. J. Vis. 23 (1), 9. https://doi.org/10.1167/jov.23.1.9.

Pavlov, I.P. (1927). Conditioned reflexes: An investigation of the physiological activity of the cerebral cortex. https://doi.org/10.5214/ans.0972-7531.1017309.

di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., Rizzolatti, G., 1992. Understanding motor events: a neurophysiological study. Exp. Brain Res. 91 (1), 176–180. https://doi.org/10.1007/BF00230027.

Poggio, T., Torre, V., 1984. Ill-Posed Problems and Regularization Analysis in Early Vision. Massachusetts Institute of Technology, Massachusetts, pp. 1–13.

Rosenbaum, D.A., Vaughan, J., Barnes, H.J., Jorgensen, M.J., 1992. Time course of movement planning: Selection of handgrips for object manipulation. J. Exp. Psychol.: Learn., Mem., Cogn. 18 (5), 1058–1073.

Schütz, C., Schack, T., 2013. Prospective and retrospective effects in a virtual pointing task. Acta Psychol. 142 (3), 314–322. https://doi.org/10.1016/j.actpsy.2013.01.005.

Tanrikulu, Ö.D., Pascucci, D., Kristjánsson, Á., 2023. Stronger serial dependence in the depth plane than the fronto-parallel plane between realistic objects: evidence from virtual reality. J. Vis. 23 (5), 20. https://doi.org/10.1167/jov.23.5.20.

Thorpe, S.J., Fize, D., Marlot, C., 1996. Speed of processing in the human visual system. Nature 381, 520–522. https://doi.org/10.1038/381520a0.

Trapp, S., Bar, M., 2015. Prediction, context, and competition in visual recognition. Ann. N. Y. Acad. Sci. 1339, 190–198. https://doi.org/10.1111/nyas.12680.

Trapp, S., Pascucci, D., Chelazzi, L., 2021. Predictive brain: addressing the level of representation by reviewing perceptual hysteresis. Cortex.

Trapp, S., Parr, T., Friston, K., Schroeger, E., 2021. The predictive brain must have a limitation in short-term memory capacity. Curr. Dir. Psychol. Sci. 30 (5), 384–390.

Turatto, M., Bonetti, F., Pascucci, D., 2018. Filtering visual onsets via habituation: a context-specific long-term memory of irrelevant stimuli. Psychon. Bull. Rev. 25, 1028–1034.

Turatto, M., Pascucci, D., 2016. Short-term and long-term plasticity in the visual-attention system: evidence from habituation of attentional capture. Neurobiol. Learn. Mem. 130, 159–169.