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Thirty years after Marr's *Vision*: Levels of analysis in Cognitive Science

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Abstract

Thirty years after the publication of Marr's seminal book *Vision* (Marr, 1982) the papers in this topic consider the contemporary status of his influential conception of three distinct levels of analysis for information processing systems, and in particular the role of the algorithmic and representational level with its cognitive-level concepts. This level has (either implicitly or explicitly) been downplayed or eliminated both by reductionist neuroscience approaches (from below) that seek to account for behaviour from the implementation level and by Bayesian approaches (from above) that seek to account for behaviour in purely computational-level terms.

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Introduction

The origin of this topic is a symposium that took place at the 34th Annual Conference of the Cognitive Science Society in Sapporo in 2012. The aim of the symposium was to acknowledge the 30th anniversary of David Marr's landmark posthumous book *Vision* (Marr, 1982) and to take the opportunity to consider the contemporary relevance of his influential conception of three distinct levels of analysis for information processing systems.

Marr's "tri-level hypothesis" (Dawson, 1998), that information processing systems can be analysed in terms of the problems that they solve (Marr's *computational* level), the representations and processes by which they solve them (the *algorithmic and representational* level), and the physical instantiation of these representations and processes (the *implementation* level) has been reformulated several times in the subsequent thirty years (e.g., Anderson, 1990; Newell, 1982; Pylyshyn, 1984) and remains a core tenet of cognitive science.

Although Marr's proposal is still widely accepted, the rapid developments that have occurred in neuroscience and Bayesian probabilistic analysis over the last decade have led to a number of questions being raised concerning the relative value of the three levels of analysis and the relationships between them. In particular, the role of the algorithmic and representational level, with its cognitive-level concepts, has (either implicitly or explicitly) been downplayed or eliminated both by reductionist neuroscience approaches that seek to account for behaviour without an algorithmic and representation level distinct from the implementation level (e.g., Bennett & Hacker, 2006) and by Bayesian approaches that model cognition using probability theory (e.g., Griffiths, Kemp & Tenenbaum, 2008; Oaksford & Chater, 2007).

This topic brings together eleven contributions that re-examine the role of the algorithmic and representational level in contemporary cognitive science. Five of those contributions (Bechtel & Shagrir; Eliasmith & Kolbeck; Gray Hardcastle & Hardcastle; Griffiths, Lieder, & Goodman; Love) are based on material presented in the symposium. Six further contributions (Anderson; Baggio, van Lambalgen & Hagoort; Bickle; Cooper &

Peebles; French & Thomas; Samuelson, Jenkins & Spencer) present perspectives not covered at the Sapporo meeting. The resulting papers represent a range of contemporary responses from the main disciplines in cognitive science, including philosophy (Bickle; Bechtel & Shagrir; Gray Hardcastle & Hardcastle), cognitive neuroscience (Love; Baggio, van Lambalgen & Hagoort), cognitive modelling (Cooper & Peebles; Love; French & Thomas), neural modelling (Eliasmith & Kolbeck; Gray Hardcastle & Hardcastle), Bayesian modelling (Griffiths, Lieder, & Goodman), dynamical systems theory (Samuelson, Jenkins & Spencer) and vision science (Anderson).

The papers

A number of themes can be discerned from the eleven papers. Two papers discuss the implications of contemporary theories of emergence for Marr's tri-level hypothesis. The first, by Samuelson, Jenkins and Spencer, does so from the perspective of dynamic systems theory (specifically dynamic field theory), and argues that the view of cognition and behaviour as the emergent outcome of the dynamic interaction of multiple components over time proposed by this approach provides a viable alternative to the traditional Marrian conception of levels of analysis starting with the computational level.

The second paper, by French and Thomas, identifies dynamic interactions across levels—in particular the bottom-up emergence of higher-level structures from lower level components, and the subsequent interactions of these emergent structures with the lower level components from which they emerge—as a property missing from Marr's analysis that contemporary cognitive science must address and explain.

Four papers discuss the relationship between theories at different levels of analysis, and in particular what constitutes an appropriate strategy for connecting models at the computational level with theories at lower levels. Griffiths, Lieder and Goodman suggest a top-down strategy which starts by generating the abstract ideal model at the computational level and then identifies models at the algorithmic and representational level that approximate the ideal solution but which are constrained in terms of the resources available.

In contrast, Love argues that the algorithmic and representational level is the

appropriate place to develop integrative theories to both the lower and higher levels. He provides examples of such integration, drawing on research in computational modeling and neuroimaging, and suggests that the blurring of the boundaries between levels created by these models may call into question the value of Marr's tripartite distinction. In a related vein, Cooper and Peebles, argue that integrated cognitive architectures such as ACT-R that provide strong, empirically grounded constraints on rational theories and also have theoretical links with neural level theories and data, are the essential bridge for linking the algorithmic and representational level to the computational and implementational levels.

The fourth paper of this type, that by Gray Hardcastle and Hardcastle, uses a case study – a neural model of the cortico-striatal circuitry held to underlie impulsivity and behavioral inhibition – to evaluate the strengths and weaknesses of each of Marr's levels from the perspective of contemporary cognitive science. While they find broad support for Marr's approach, they also argue for some updating of it. First, they suggest that Marr's computational level should be extended to include a description of how the system breaks down following neural damage. Second, they emphasize that cognition is not a feed-forward process that is disconnected from behavioral context and driven by the transformation of representations (as the Marrian approach assumes). This suggests greater interaction between levels than might follow from a simplistic application of Marrian analysis.

A third theme concerns the nature of specific levels, and in particular the nature of the computational level. While approaches to this level based on probability theory supplemented with Bayes' theorem have been the focus of much recent work (e.g., Griffiths et al., 2008; Oaksford & Chater, 2007), this approach has itself also been a target of much recent criticism (e.g., Bowers & C. J. Davis, 2012; Eberhardt & Danks, 2011; Jones & Love, 2011; Marcus & E. Davis, 2013). Two papers in this topic take issue with Bayesian accounts of the computational level. Anderson notes the goal-directed nature of the computational level and criticizes many contemporary (primarily Bayesian) accounts for failing to distinguish between tasks shaped by natural selection and evolutionary "by-products". In contrast, Baggio, van Lambalgen and Hagoort argue that propositional logic provides a more satisfactory account of the computational level than probability theory, linking accounts

based on logic to other levels through behavioral and neural data.

Three papers present contrasting views on the question of whether all three of Marr's levels are necessary. Bickle claims that advances in molecular biology and neuroscience support reductionist explanations of cognitive functions which eliminates the need for algorithmic and representational and computational explanations. In contrast, Bechtel and Shagrir argue that each of Marr's three levels makes an important and non-redundant contribution to cognitive explanation, particularly in understanding environmental influences on cognitive mechanisms. Finally, Eliasmith and Kolbeck argue that, contrary to some interpretations, Marr sought to integrate his three levels, with each providing constraints on the others, and use their own work to demonstrate the integration of high-level functional and detailed mechanistic explanations.

This summary of themes does not do justice to the integrative nature of many of the contributions. For example, Love also touches on this issue of the necessity (or otherwise) of all levels, while Gray Hardcastle and Hardcastle also consider relations between levels with their neural model of cortico-striatal circuitry. However, it is clear from the contributions that 30 years on many researchers still consider that Marr's levels are essential to cognitive scientific explanation. That is, there remains broad agreement that neither the computational level nor the implementation level (alone or in conjunction) can provide a full account of cognitive processes, and the algorithmic and representational level remains essential to bridge between implementation and function.

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