Cognition 174 (2018) 1–18

Contents lists available at ScienceDirect

Cognition

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

Original Articles

Contour interpolation: A case study in Modularity of Mind

Brian P. Keane*

Rutgers University, Robert Wood Johnson Medical School, 671 Hoes Lane West, Piscataway, NJ 08854, USA
Rutgers University, Center for Cognitive Science, 152 Frelinghuysen Road, Piscataway, NJ 08854, USA
Rutgers University, University Behavioral Health Care, 671 Hoes Lane West, Piscataway, NJ 08854, USA

ARTICLE INFO

Keywords:
Modularity
Contour interpolation
Contour integration
Illusory contours
Amodal completion
Salience

ABSTRACT

In his monograph *Modularity of Mind* (1983), philosopher Jerry Fodor argued that mental architecture can be partly decomposed into computational organs termed modules, which are characterized as having nine co-occurring features such as automaticity, domain specificity, and informational encapsulation. Do modules exist? Debates thus far have been framed very generally with few, if any, detailed case studies. The topic is important because it has direct implications on current debates in cognitive science and because it potentially provides a viable framework from which to further understand and make hypotheses about the mind's structure and function. Here, the case is made for the modularity of *contour interpolation*, which is a perceptual process that represents non-visible edges on the basis of how surrounding visible edges are spatiotemporally configured. There is substantial evidence that interpolation is domain specific, mandatory, fast, and developmentally well-sequenced; that it produces representationally impoverished outputs; that it relies upon a relatively fixed neural architecture that can be selectively impaired; that it is encapsulated from belief and expectation; and that its inner workings cannot be fathomed through conscious introspection. Upon differentiating contour interpolation from a higher-order contour representational ability ("contour abstraction") and upon accommodating seemingly inconsistent experimental results, it is argued that interpolation is modular to the extent that the initiating conditions for interpolation are strong. As interpolated contours become more salient, the modularity features emerge. The empirical data, taken as a whole, show that at least certain parts of the mind are modularly organized.

> *"[Although] great and extraordinary men have gone before me…I am not without some hopes, upon the consideration that the largest views are not always the clearest, and that he who is short-sighted will be obliged to draw the object nearer, and…by a close and narrow survey discern that which had escaped far better eyes."*
> George Berkeley (1734/1996), A Treatise Concerning The Principles of Human Knowledge

1. Introduction

In his seminal book *Modularity of Mind* (1983), Jerry Fodor postulated perceptual and linguistic mechanisms that can be characterized by a cluster of nine co-occurring features. Modules are domain specific in that they solve a specific computational problem and respond to a narrow range of input. They are informationally encapsulated in that the cognitive information that they bring to bear on the problem is limited in comparison to what could be deployed. Modules mature in an innately paced manner such that there will be characteristic milestones at which time one or more capacities come on line. They rely upon fixed neural circuitry that can be selectively impaired. Modules obligatorily and rapidly generate output upon receiving specific types of input. Central access to the goings-on of a module is limited in that we cannot introspectively discern the rules that a module implements. Modular outputs are also shallow; they cannot express conceptual content and certainly cannot express sophisticated phenomena such as whether an image is of a "proton trace", to use Fodor's example (e.g., pp. 86, 93).

Fodor's thesis has generated enormous controversy in a diverse array of disciplines such as linguistics, philosophy, anthropology, computer science, and evolutionary biology. As with many broad ranging debates in cognitive science, the topic has created more controversy than consensus. Some have argued that moral cognition, music cognition, theory of mind, or syntactic judgments take on some of the properties that Fodor originally described (Fedorenko, Behr, & Kanwisher, 2011; Haidt & Joseph, 2007; Scholl & Leslie, 1999). Others have argued that the evidence for a modular mind is scant at best and that the whole concept offers little help in cognitive science (Prinz,

* Address: Rutgers, The State University of New Jersey, USA.
E-mail address: Brian.Keane@Rutgers.edu.

https://doi.org/10.1016/j.cognition.2018.01.008
Received 2 October 2017; Received in revised form 17 January 2018; Accepted 18 January 2018

2006). A problem is that the debate has been framed in very general terms with few, if any, detailed case studies. Moreover, many of the debates have drifted from Fodor's original formulation. Some, including Fodor himself, have maintained that informational encapsulation is at the heart of modularity (Fodor, 2001), others have argued that functional (domain) specificity is the most important criterion (Barrett & Kurzban, 2006; Coltheart, 1999; Pinker, 2009), while still others have emphasized the mind's relatively fixed and functionally specialized neural circuitry (Kanwisher, 2010). What is needed and what I provide here is a *detailed* case study of a mechanism that fits Fodor's original and much broader formulation.[1]

There are several reasons why it is valuable to re-inspect Fodor's original modularity thesis. One is that it directly impinges on more specific controversies in cognitive and vision science. Firestone and Scholl (2015) have vehemently argued that perception is encapsulated from high-level cognition and that alleged counterexamples suffer from serious methodological flaws. Establishing a module would obviously strengthen their position. Likewise, some have argued for the functional specialization of numerous brain regions (e.g., the fusiform face area) whereas others have upheld the opposite view (Hanson & Schmidt, 2011; Kanwisher, 2010; Pitcher, Charles, Devlin, Walsh, & Duchaine, 2009). The modularity perspective, again, takes a stand. Fodorian modularity also implies that certain perceptual or cognitive abilities unfold in an orderly manner over the course of normal development, and that these are "surprisingly insensitive to deprivation of environmental information" (Fodor, 1983, p. 100). This claim too is subject to ongoing investigation (Gandhi, Kalia, Ganesh, & Sinha, 2015; Murray, Matusz, & Amedi, 2015). The relevance of modularity to these and other important questions may explain why Fodor's book has garnered over 14,000 Google Scholar citations to date, with more than 500 in 2017 alone.

Another reason to value the modularity thesis is that it yields a broad theoretical framework in which to couch an understanding of the mind and from which to formulate new testable predictions. Establishing a module would raise questions such as: How or in virtue of what do the modularity features co-occur? What stimulus conditions are needed to activate a module? What happens in the brain computationally and physiologically when a process expresses or fails to express modularity features? Do modules make organisms more evolvable in the face of direct selection pressures (Clune, Mouret, & Lipson, 2013)? Are modules like tiny islands in the vast ocean of equipotentiality or are they instead like phrenological continents sprawled across neocortex? Therefore, because Fodorian modularity has ramifications for how the mind works and how it can be investigated, and because it continues to be relevant in ongoing debates, Fodor's framework should be seriously scrutinized by practicing vision and cognitive scientists.

In the upcoming discussion, I focus specifically on *contour interpolation*, which is a visual process that represents non-visible edges on the basis of how surrounding physically visible edges are spatiotemporally configured. I use the term "interpolation" in a generic sense to include any instance where multiple non-contiguous edge elements are combined to form a greater contour and where the inter-element gap must be "filled-in", that is, treated as if it contained something physically visible (Fig. 1). Examples include combining spatially segregated oriented edge segments into a unified boundary (contour integration), forming illusory contours between locally aligned elements (modal completion), completing a contour behind an occluding surface (amodal completion), and seeing a line that emerges from a series of line endings (Varin, 1971). I do not consider more exotic forms of interpolation such as when an observer must move his or her head or body to see the integrated elements, nor do I include instances of contour extrapolation (Halko, Mingolla, & Somers, 2008; Singh & Fulvio, 2005). Therefore, the focus is on the basic boundary formation process that ensues when the visual system is confronted with two or more appropriately aligned, spaced, and oriented edge elements.

Interpolation is of interest because it is a *prima facie* likely candidate for modularity. It plays a critical role in normal seeing, helping to recover the shape, number, size, and persistence of objects that linger in our field of view (Kellman & Shipley, 1991). A canonical illusory or "Kanizsa" square (Fig. 1A) is seen not as four notched circles but as four complete circles partially occluded by a shape whose color and texture matches that of the background (Fig. 1A) (Kanizsa, 1955). A partly occluded bar is seen not as two dangling objects abutting a common surface, but as a single entity poking out from behind (Fig. 1B). A shape gliding behind a holed occluder is experienced as a single, gradually-appearing object rather than as a kaleidoscope of individual elements that flash in and out of existence (Fig. 1H) (Keane, Lu, & Kellman, 2007; Palmer, Kellman, & Shipley, 2006). Four line segments that translate back-and-forth orthogonally to their respective slant directions are perceived as a single orbiting diamond rather than as four unrelated motion events (Fig. 1G) (Lorenceau & Alais, 2001; Lorenceau & Shiffrar, 1992). These distal properties of object shape, number, size, and persistence are arguably among the most important to recover; depriving the visual system of such features would wipe out much of what distinguishes vision from the other senses.[2] If any function should be hardwired into our cognitive architecture, interpolation should be chief among them. Underscoring interpolation's importance is its sweeping prevalence in the animal kingdom: mice, fish, bees, sharks, newborn chicks, and countless other species all rely upon the process (Fuss, Bleckmann, & Schluessel, 2014; Kogo & Wagemans, 2013; Nieder, 2002; Nieder & Wagner, 1999; Regolin & Vallortigara, 1995).

A module should also be suspected whenever a complex function would be difficult or cumbersome to perform on the fly within behaviorally relevant time scales. Interpolation's function again is suggestive. It impressively determines at each moment how hundreds of scene segments form contours and closed surfaces (objects) (Field, Hayes, & Hess, 1993; Hess, Hayes, & Field, 2003). Leaving this computationally daunting task to the vicissitudes of a slow and effortful "system 2" type of mechanism (Kahneman, 2011) would seem impractical given the dynamics of natural scenes and the retina's constantly changing spatial relation to the distal layout.

A pragmatic reason to consider interpolation is that we know a lot about it. A PubMed search for a union of relevant terms yielded 863 results (terms—"contour integration", "illusory contours", "amodal completion", "modal completion", "subjective contours", "contour interpolation", "contour completion", "boundary completion"; search date—9/29/2017). The search dramatically underestimates the volume of research on the topic not just because it excludes books, periodicals, and non-English journals, but also because many more generic or unusual key terms could have been included but were not, including "perceptual completion", "visual completion", "phenomenal contours", "quasiperceptive contours", "visual binding", and "feature binding", to name a few. A bibliography compiled over 25 years ago found 445 entries on subjective contours alone (Purghé & Coren, 1992). The jury should now be in as to whether interpolation qualifies as a module.

In what follows, I go through Fodor's nine criteria to make the case that contour interpolation fits his original description. The evidential base from which I construct my argument is necessarily broad in scope, incorporating a variety of methodologies—psychophysics, TMS, fMRI, EEG, eye movements, lesion studies, single-cell recording, two photon

[1] While there have been case studies using Fodor's original definition such as that by Wagemans on visual shape determination (1988, pp. 67–75), few, if any, go into detail for each feature. Moreover, the present work has the luxury of being able to draw upon a larger and more recent literature (> 800 articles; see below) and thus can benefit from the full gamut of findings from modern neuroscience, psychology, and related disciplines.

[2] The spatial character of audition, while important, lacks higher spatial frequency content and thus holds less value for determining object shape, number, and size. Moreover, in contrast to haptic perception, vision recovers properties of the *distal* environment, which do not immediately impinge on the transducing organs.