Multiple Realization and Methodology in the Neurological and Psychological Sciences.

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The reigning picture of special sciences, what we will term the 'received' view, grew out of the work of writers, such as Jerry Fodor, William Wimsatt, and Philip Kitcher, who overturned the Positivist's jaundiced view of these disciplines by looking at real cases from the biological sciences, linguistics, psychology, and economics, amongst other areas.[1] Central to the received view is the ontological claim that the 'multiple realization' of properties is widespread in the special sciences which we may frame thus:

(a) The properties studied by the special sciences are multiply realized by the properties studied by lower-level sciences.

Furthermore, building upon (a) in different ways, the proponents of the received view provided devastating critiques of the Nagelian model of reduction and the associated idea of the Positivists that, ultimately, special sciences could be dispensed with in favor of physics. The resulting conclusion, and arguably the second core claim of the received view, is that the predicates of special sciences, and hence these disciplines themselves, are, in principle, indispensable. Let us frame this thesis as follows:

(b) Special science predicates, and hence the explanations, theories and sciences using these predicates, are, in principle, indispensable.[2]

The ontological phenomenon of multiple realization was thus used to produce significant advances which reshaped our picture of special sciences and the core claims of the

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[1] See, for example, Fodor (1968), (1974), and (1975); Kitcher (1984); and Wimsatt (1974), (1976) and (1994), amongst many others.

[2] This claim should be read as concerning kinds of predicates, rather than particular predicates, since it is obvious that specific predicates are constantly being replaced in all of the sciences as they progress.

received view are still at the heart of many key debates in the philosophy of science and the philosophy of mind.

Given the continued philosophical importance of the received view, it is perhaps unsurprising that the existence of multiple realization, most particularly in the neurological and psychological sciences, has recently been challenged by a growing number of writers, including Jaegwon Kim ((1992), (1999)), William Bechtel and Jennifer Mundale (1999), Brian Keeley (2000), John Bickle (2003), Thomas Polger (2004), Laurence Shapiro ((2000), (2004)), and others.[3] In this paper our goal is to carefully evaluate the most important of these critiques.

At this preliminary stage, it is worthwhile carefully noting some qualifications about our project in order to avoid confusions with superficially similar programs. First, we want to emphasize that we are considering only the first-order descriptive issues of the nature of the relations between properties posited in the special sciences, the methodology of the special sciences, and any connections between the two. We make no claims about how such findings impact second-order philosophical disputes, for example over reductionism, since we believe examining such secondary issues often muddles already complex discussions. Second, we are interested here in only one strand of the previous defenses of multiple realization in the special sciences. As some critics rightly note, in earlier debates there were a variety of defenses of multiple realization, namely, those using thought-experiments and unvarnished conceivability claims, and those employing the best scientific evidence of the time. The former arguments, found most obviously in the work of Hilary Putnam ((1967), (1975a)), face important challenges. We

[3] See also McCauley and Bechtel (2001) and Revonsuo (2001), amongst others.

will solely be concerned with whether our empirical evidence supports multiple realization, thus following writers such as Fodor, Wimsatt and Kitcher.

Third, corresponding to the various arguments used in their defense, claims about multiple realization are of widely differing strengths. Here we will only defend the following thesis, 'Human Psychological Multiple Realization' (HPMR):

> (Human Psychological Multiple Realization) In organisms of the species *Homo sapiens*, many instances of the same psychological properties are realized by instances of distinct neural properties within the same, and different, organisms.

We also endorse the claims associated with HPMR that, in humans, psychological individuals and mechanisms are, respectively, multiply constituted and multiply implemented by neural individuals and mechanisms. In fact, we contend that multiple realization, multiple constitution and multiple implementation are prevalent for the psychological, neural and biochemical properties of most terrestrial species. However, though we have defended these wider claims elsewhere, in order to keep our discussion manageable we will here focus only upon defending HPMR.[4]

There are a number of distinct, though inter-connected, arguments against the existence of multiple realization. We will examine what we take to be the two most important kinds of critical arguments, one methodological and the other ontological, in order to build our over-arching assessment of recent critiques and as a foil against which to articulate our own positive view. After outlining the key kind of scientific cases, in Part 1, we will provide a metaphysical account of realization and use it to frame the claims of the received view and the empirical evidence supporting HPMR. Against this

[4] For example, see Aizawa (Forthcoming) for reasons to believe, contrary to Bickle (2003), that multiple realization, multiple constitution and multiple implementation are prevalent for the psychological and neural properties of most terrestrial species.

background, in Part 2, we will then examine the most common critique of multiple realization. In what we will term the 'Methodological Argument,' multiple realization is rejected on the basis of its putative methodological implications. After reconstructing this argument, we will show that it is based upon a mistaken thesis about the methodological implications of multiple realization. We will then briefly digress, in Part 3, to consider the exegetical question of the position actually taken by defenders of the received view and we will suggest that the received view has been widely misinterpreted. Lastly, in Part 4, we consider what we dub 'Metaphysical Arguments' against the multiple realization of scientifically legitimate properties and show that they also fail because they are question-begging and also ultimately depend upon a flawed view of scientific realization relations.

We will conclude by drawing our findings together into an over-arching account of multiple realization, and its implications for methodology, in the neurological and psychological sciences, as well as the specials science generally. As will become clear, our final positive view encompasses some of the key points defended by the most strident critics of multiple realization. Most obviously, we will defend the importance of inter-theoretic constraints, and other methodological connections, between the neurological and psychological sciences. For example, we will endorse the utility of what has been termed a 'co-evolutionary research strategy' for these disciplines. However, in contrast to recent critics, we will argue that these methodological connections are the results of multiple realization. For we will show that the nature of multiple realization itself, as well as evidence from the special sciences, implies that the sciences studying realizer and realized properties inter-theoretically constrain each other. Thus, although endorsing the significance of many of their points, our main conclusion will consequently be that its recent opponents fail to establish that multiple realization does not exist. On the contrary,

we will show that in most cases the evidence offered by critics is either compatible with, or in fact further confirms, the truth of HPMR and the widespread existence of multiple realization in the neurological and psychological sciences.

Part 1 – Mechanisms, Realization and Multiple Realization.

To understand the questions at issue, and also the key claims of the received view, it will help if we start by considering an actual case of realization from the neurosciences.[5] For example, we know that, under appropriate background conditions, voltage-sensitive potassium ion channels play a key role in neurons by quickly allowing the passage of potassium ions whilst blocking other ions. And the sciences have provided a compelling mechanistic explanation of how such ion channels do this in terms of the properties and relations of the complex protein molecules that are 'sub-units', i.e. parts, of these channels. In this case, putting things very crudely, we know that, under the relevant background conditions, the chemical properties and spatial alignment of the complex protein sub-units mean that the sub-units change their relative spatial positions in very particular ways when there are changes in the charge of adjacent cells. (See Figure 1 for a textbook illustration of the structure of the sub-units taken from Levitan and Kaczmarek (2002), p.111). Basically, when the charge changes, then the sub-units adopt new spatial relations to each other which leave them together forming a 'gate' such that the chemical properties of the individual protein sub-units facilitates the fast passage of potassium ions, whilst blocking other ions.

[5] Following the recent metaphysical debates over realization, we will assume a causal theory of properties under which a property is individuated by the powers it potentially contributes to individuals. We will thus use a version of Shoemaker (1980)'s account and to cover as many participants in the debate as possible we shall take this commitment to be the relatively weak view that in the actual world all instances of a property contribute the same powers under the same conditions.

In this case, we have a range of compositional relations between properties, individuals and mechanisms at different levels. The mechanisms involving the constituent protein molecules changing spatial position together implement the mechanism of the ion channel allowing speedy passage of potassium ions. We also have part-whole, or constitution, relations between the ion channel and protein sub-units. And, most importantly for our purposes, we also have so-called 'realization' relations between the properties and relations of these individuals. With regard to the ion channel, the properties and relations of the sub-units, such as their alignment and chemical properties, 'play the causal role' of the ion channel's property of allowing speedy passage of potassium ions – basically, the powers contributed by the lower level properties *together* non-causally result in the powers of the realized property. We can therefore offer this 'thumbnail' account of realization, elsewhere dubbed the 'Dimensioned' view:[6]

> (Dimensioned Realization) Property/relation instance(s) F_1-F_n realize an instance of a property G, in an individual *s* under condition $, *if and only if s* has powers that are individuative of an instance of G in virtue of the powers contributed, under $, by F_1-F_n to *s* or *s*'s constituent(s), but not vice versa.

The Dimensioned account nicely covers key features of the realization relations found in the ion channel case, and similar examples involving mechanistic explanations found throughout the special sciences. For this view allows realizer and realized properties to be instantiated in different individuals, like the ion channel and the sub-units, where realizer properties together play the causal role of the realized property without directly contributing any of the realized property's individuating powers. We should carefully

[6] This 'thumbnail' account of realization is defended, and developed, in Gillett (2002) and (2003). However, a full-blown account of scientific realization, as part of an integrated account of the compositional relations between powers, properties, individuals and mechanisms, is offered in Gillett (Unpublished).

mark that this determination relation is not temporal in nature, since the upward determination involved in realization is instantaneous. That it does not relate wholly distinct entities. And that realization does not involve the transfer of energy and/or mediation of force. It therefore appears that realization is *not* a species of causal determination, since causal relations are temporally extended, involve wholly distinct entities and do usually involve the transfer of energy and/or mediation of force. We have therefore taken realization to be an example of what we term *'non-causal'* determination, like the relations between the individuals bearing part-whole or constitution relations, or the implementation relations between processes.

We will begin by assuming the Dimensioned account of realization, since it fits well with scientific cases of realization and also helps to illuminate the claims of the received view. (Later, in Part 4, we will explicitly consider a competing view of the metaphysics of realization relations in the sciences). The Dimensioned picture of realization highlights the nature of both HPMR, and the more general claim embodied in thesis (a) of the received view, since writers such as Fodor, Wimsatt and Kitcher have all emphasized that constituents with very different properties and relations can *together* realize distinct instances of the very same special science property – whether the property is having monetary value, or being a gene, or any of a host of other special science properties – hence leading to the *multiple* realization of such properties. With each instance of such a multiply realized special science property, call it 'E', there are lower level realizer property/relation instances, instantiated in lower level individuals, which are such that their contributions of powers together suffice for all the powers of E in some higher level individual. Obviously, given the multiple realization, heterogeneous realizer properties are often responsible, usually in distinct individuals, for contributing the

powers that result in the powers individuative of E. Nonetheless, however heterogeneous the different types of realizer property may be in their contributions of powers, with each instance of E the relevant realizers always contribute disparate powers that together all result in the *same* powers in the higher individual, i.e. the powers individuative of E.[7]

With regard to HPMR, numerous empirical grounds were used by proponents of the received view in order to defend this thesis. For example, Block and Fodor (1972) present three types of considerations supporting the multiple realization of psychological properties -- evidence from the neurological sciences, convergent evolution, and the conceptual possibility of machine minds. Obviously here we are concerned with the neurological evidence about which Block and Fodor claim that:

> First, the Lashleyan doctrine of neurological equipotentiality holds that any of a wide variety of psychological functions can be served by any of a wide variety of brain structures. While the generality of this doctrine may be disputed, it does seem clear that the central nervous system is highly labile and that a given type of psychological process is, in fact, often associated with a variety of distinct neurological structures. For example, though linguistic functions are normally represented in the left hemisphere of right-handed persons, insult to the left hemisphere can lead to the establishment of this function in the *right* hemisphere. (Of course, this point is not *conclusive*, since there may be some neurological property in common to the structures involved.) (Fodor & Block, 1972, p.238)

Furthermore, Fodor (1974) points in the direction of two possible ways in which psychological processes could turn out to be multiple realized in neurological structures:

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[7] See Gillett (2003) for a more detailed treatment of the nature of this view of multiple realization and its implications.

> It is entirely possible that the nervous system of higher organisms characteristically achieves a given psychological end by a wide variety of neurological means. It is also possible that given neurological structures subserve many different psychological functions at different times, depending on the character of the activities in which the organism is engaged. In either event, the attempt to pair neurological structures with psychological functions could only expect limited success (Fodor, 1981, p. 135).

By and large, subsequent developments in neuroscience have been consonant with the core contention of the received view as applied to the neurological and psychological sciences – namely, that instances of a given psychological property are often realized by distinct neural properties.

Recent neurological research on a variety of different cognitive processes can be used to support the latter point, whether neuroanatomical studies of primates and other mammals or neuroimaging work with human subjects. To illustrate the detailed nature of such evidence we will focus on the evidence that comes from experimental work on visual area V1 of macaques, cats, and mice. In a classic study, David Hubel and Torsten Wiesel found that as microelectrodes pass through layers of V1, they encounter neurons whose receptive fields for a given location have "scattered" orientations. Although there are some recurring patterns within the scattered receptive fields, such as cells with large receptive fields very nearly adjacent to each other, the scattering of cells varies from organism to organism of the same species. (See Figure 2, reproduced from Hubel and Wiesel (1974), p. 297). Insofar as the psychological properties of V1 are realized by these underlying neuron circuits, variations in these circuits across individuals suggest that there are distinct neural realizations of psychological properties.

A more recent technique of optical imaging reinforces the same point. Active cortical tissue differs in appearance from inactive cortical tissue. Sensitive cameras can record these differences in the appearance of the exposed cortex of an actively observing macaque. Optical imaging reveals that adjacent regions of brain tissue are sensitive to particular oriented lines and bars, but that the details of these regions vary from individual to individual. There are, of course, regularities in these regions, such as the presence of so-called "pinwheels," but again it appears that there are individual differences in the connectivity patterns among neurons. (See Figure 3, reproduced from Kandel, Schwartz, and Jessell (2000), p. 538). Such individual differences again point towards distinct realizations. Furthermore, Horton and Hocking (1996) use cytochrome oxidase staining in a study explicitly designed to document the variability of ocular dominance columns in normal macaque monkeys. Figure 4 below shows the variability in size of ocular dominance columns in macaques.[8]

Finally, still more recent, and cutting-edge, techniques have enabled neuroscientists to insert fluorescent proteins into particular neurons and microscopically observe the structure of these neurons over the course of days, weeks, and months. The drift of these findings is that in area V1 there is a high degree of stability of overall neuronal structure and in the majority of dendritic spines (mushroom-shaped structures that contain one or more excitatory synapses). Nevertheless, even in adults dendritic spines are dynamic. A small percentage of spines appear or disappear over the course of months (Grutzendler, Kasthuri, and Gan (2002), p. 814). Moreover, spines vary in length and head diameter over 3-day and 1-month periods. Insofar as these changes in spine morphology are correlated with changes in postsynaptic density and the magnitude of

[8] Figure 4 is modeled on Horton and Hocking (1996)'s Figure 2.

signals transmitted to the neuronal cell body, these changes could plausibly modulate synaptic efficiency (Grutzendler, Kasthuri, and Gan (2002), p. 814).[9] Changes in spine number and morphology could, therefore, plausibly underlie distinct realizations of psychological properties and mechanisms.

It would, of course, be desirable to be able to link the foregoing kinds of variations in neuronal properties to variations in the causal powers of neurons and relate these, in turn, to a particular, higher-level cognitive property and its individuating powers. But, as yet, contemporary neuroscientific research has not reached a consensus on important features of the structure and function of human V1, much less the whole of the human cortex. Nevertheless, empirical work on non-human animals suggests that there are individual variations in the structure of neuronal networks in human V1. And such variation is heavily supported by findings with every brain mapping technique used over the last century, including neuroimaging research on humans.[10] This, in turn, suggests that there are individual variations in the structure of neuronal networks throughout the human cortex and insofar as these differences contribute to the realization and implementation of unitary higher-level psychological properties and mechanisms, we therefore have scientific evidence for the multiple realization, and multiple implementation, of human psychological properties and mechanisms by neural properties and the mechanisms associated with them.

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[9] Other studies suggest comparable findings in mouse somatosensory cortex. See for example Trachtenberg et al. (2002), Zuo et al. (2005), and Holtmaat et al. (2005).

[10] Amunts, et al., (2000), present cytoarchitectonic data showing the individual variation in the size of the human V1 and V2. van Essen, et al. (1984), use single cell electrophysiological methods to document individual variation in macaque V1. Frackowiak, et al., (1997), describe mathematical techniques that are routinely used to factor out, or normalize, individual variations among human subjects in PET and fMRI. Studies using one or another of these methods are legion. Denys, et al., (2004), for example, presents fMRI data showing individual variations in regions sensitive to shape, to motion, and to shape and motion.

In kind with the evidence provided by the previous generation of neurophysiologists like Lashley, contemporary developments in the neurosciences have thus provided empirical support for the key contention made by defenders of the received view. For we have now seen that a prima facie plausible case can be made that we have good empirical evidence for HPMR and its claim that a given type of psychological property, or process, in humans is often realized, or implemented, by a variety of distinct neurological properties and mechanisms.

Part 2 – The Methodological Arguments against Multiple Realization.

With a better grip on the claims of the received view about multiple realization, we can now turn to perhaps its most prominent critique. This is what we will term the 'Methodological Argument' against multiple realization, offered in Bechtel and Mundale (1999), and Shapiro (2004), amongst others, and which is grounded upon evidence about actual cases of inter-theoretic constraint in the neurological and psychological sciences. For reasons that will become clear very quickly, in order to understand the nature of this critical argument we first need to see how recent critics take the received view to defend the so-called 'autonomy' of the special sciences.

Like many other critics of the received view, Bechtel and Mundale start their interpretation and critique of this position by considering the work of Hilary Putnam who first brought the phenomenon of multiple realization to philosophical attention using thought experiments about the range of individuals, whether alien or artificial intelligences, whose properties it is claimed we can conceive of as realizing psychological properties (Putnam (1967), (1975a)). Bechtel and Mundale consequently tell us what their focus will be:

> The claim, originating with Hilary Putnam, that psychological states are multiply realizable, has become orthodoxy in the philosophy of mind… Our primary concern… is with the implication drawn from the multiple realizability argument that information about the brain is of little or no relevance to understanding psychological processes. (Bechtel and Mundale (1999), p.176)

The conjunction of the ontological phenomenon of multiple realization, and the lack of methodological connections between the neurological and psychological sciences, is a natural one to draw from Putnam's work. For Putnam stated that, given their multiple realizability, the realization of psychological properties does not matter – infamously, Putnam went so far as to suggest that "We could be made of Swiss cheese and it wouldn't matter" (Putnam 1975a, p.291). The resulting picture of the ontology of the special sciences, and their methodology, is nicely framed by Shapiro who tells us:

> …even though philosophers no longer think of minds as supernatural things – as things that exist outside space and time – many do adhere to a conception of the mind-body relationship that seems to offer little more than a naturalized version of the ghost in the machine… Because minds can be realized in a vast variety of kinds of things, one has the sense that minds and brains are connected only loosely, and with a little tugging, or if the wind blows strongly enough, the two will go their separate ways. (Shapiro (2004), p.ix-x)

This combination of views, and the resulting view of the ontology and methodology of the special sciences, is what we shall term, following Shapiro, 'Ghostly Multiple Realization'. And though Ghostly Multiple Realization is apparently a view primarily drawn from Putnam's work, the position is widely ascribed to the received view of special sciences defended by writers like Fodor, Wimsatt and Kitcher. In the next section

we will consider the exegetical question of whether Ghostly Multiple Realization is actually endorsed by defenders of the received view. But we now want to lay-out the defense of the so-called 'autonomy' of the psychological sciences that critics like Shapiro, Bechtel and Mundale, and many others, consequently ascribe to the received view as a result of interpreting this position as endorsing Ghostly Multiple Realization.

At the heart of this reasoning is a methodological application of the claim, drawn from Putnam, that given multiple realization the nature of the realizers of psychological properties simply does not matter for the psychological sciences. The precise character of the methodological implications in question will not be central to the issues we will examine, so we will simply use 'M' to denote the relevant form(s) of inter-theoretic constraint. (Similarly, we will leave the notion of 'autonomy' undefined for the present). The thesis consequently ascribed to Ghostly Multiple Realization, and hence to the received view, is what we will call the 'No Constraint Principle', or often simply the 'Principle', that is stated thus:

(1) If properties H1-Hn are multiply realized by properties L1-Ln, then there is no inter-theoretic constraint of type M between the science(s) studying properties L1-Ln and the science(s) studying properties H1-Hn.[11]

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[11] The No Constraint Principle, and hence our premise (1), are thus meant to be a generalization of claims by recent critics, for example the following kinds of contention made by Bechtel and Mundale:

> For multiple realization to be a serious option, brain taxonomy would have to be carried out both independently of psychological function, and without comparative evaluation across species (Bechtel and Mundale (1999), p. 177)

And such claims as these from Shapiro (see also Shapiro (2004), p.72, amongst many others):

> The multiple realizability thesis and the separability thesis make predictions about what we can predict about that which realizes the mind (i.e. the brain) and that which contains the mind (i.e., the body). If the former is true, it should not be possible to predict many or any

A second premise is then drawn from thesis (a) and defenders of the received view are hence also taken to endorse this claim:

(2) Psychological properties are multiply realized by neural properties.

Since psychology and cognitive science study psychological properties, and the neurosciences study neural properties, from (1) and (2) it can therefore be concluded that:

(C1) There is no inter-theoretic constraint of type M between psychology and cognitive science, and the neurosciences.

Using such an argument, the putative multiple realization of psychological properties by neural properties, in combination with the No-Constraint Principle, produces in (C1) a key claim ascribed by recent critics to the received view – namely, a strong form of methodological 'autonomy' for the psychological sciences. We shall therefore call this the 'Argument for Autonomy' and it forms the backbone of the Ghostly Multiple Realization view of the special sciences.

It is important to appreciate the nature of Ghostly Multiple Realization, and the Argument for Autonomy, for they illuminate the background against which the Methodological Argument against multiple realization is offered by both Shapiro and Bechtel and Mundale. For in response to these doctrines, the critics do an impressive job of marshalling a detailed array of actual examples from the neurological and psychological sciences that demonstrate that there is actual inter-theoretic constraint

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> properties of the mind's realizer. It should not be possible, that is, to predict, from a description of the mind's capacities, what properties the mind's realizer must possess (Shapiro (2004), p. xi).

As should be clear from the latter passage, Shapiro uses a variant of the No Constraint Principle, i.e. premise (1), which bars *both* ontological *and* methodological constraints between sciences studying realizers and realized properties. Throughout we will focus on the Principle, but we will see below that the same worries that apply to the methodologically-focused Principle also apply to Shapiro's arguments based around his still stronger thesis.

between these disciplines in all kinds of contexts.[12] For reasons that will become clear below, we are happy to endorse the veracity of such evidence about actual inter-theoretic constraint between these sciences. Instead, we are more concerned about the argument that the critics of multiple realization base around such evidence. For Shapiro, and Bechtel and Mundale, both use these findings to attack the existence of multiple realization by turning the key premise of the Argument for Autonomy, in the No Constraint Principle, back upon their perceived opponents. The resulting argument has the following structure:

(1) If properties H1-Hn are multiply realized by properties L1-Ln, then there is no inter-theoretic constraint of type M between the science(s) studying properties L1-Ln and the science(s) studying properties H1-Hn. (No Constraint Principle)

But the range of evidence about inter-theoretic constraints in the actual scientific cases illuminated by Shapiro, and Bechtel and Mundale, also makes it highly plausible that:

(2*) There is inter-theoretic constraint of type M between psychology and cognitive science, and the neurosciences.

Therefore, from (1) and (2*), and assuming psychology and cognitive science study psychological properties, the neurosciences study neural properties, and neural properties realize psychological properties, we may conclude:

(C2) Psychological properties are not multiply realized by neural properties.

This is what we earlier termed the 'Methodological Argument' against multiple realization. Through such reasoning critics can obviously use their evidence about actual inter-theoretic constraint between psychology and the neurosciences in combination with the No-Constraint Principle, a claim that the critics assume is the key tenet of their

[12] See especially sections 2, 3 and 4 of Bechtel and Mundale (1999) and chapters 3 and 4, as well as 6 and 7, in Shapiro (2004).

opponent's perceived 'Argument for Autonomy', to conclude that the multiple realization of psychological properties by neural properties simply does not exist.[13]

The Methodological Argument is clearly important, not least because it is so common, but we can immediately see that something is dialectically awry. For the critics of multiple realization who offer this argument also often endorse evidence that makes HPMR, and hence the existence of the ontological phenomenon of multiple realization, prima facie plausible. Bechtel and Mundale (1999) provide perhaps the clearest case for our purposes, since in the course of their discussion they highlight the large body of empirical evidence supporting variation in the neural properties that realize the same psychological properties in the same, or different, individuals of a species. For example, they rightly note, as we emphasized in Part 1, that we have strong evidence from neuroanatomical research, on primates and other species, for variation in neural realizers across the individuals even of the same species (Bechtel and Mundale (1999), p.177 and p.179). And they also acknowledge the evidence from neuroimaging studies on humans that also supports variation of neural realizers in human subjects (Bechtel and Mundale (1999), p.190). Clearly this is somewhat odd, for how can these critics endorse the main empirical evidence that we saw in Part 1 supports multiple realization and yet still go on to deny the existence of multiple realization?

We can begin to identify what has gone wrong in the debate if we more carefully consider the ontological nature of realization relations and their methodological implications. As we saw in Part 1, realization is a species of determination relation, albeit

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[13] Obviously Shapiro (2004) also runs similar arguments against multiple realization using the ontological constraints between neural and psychological properties that he outlines in combination with the stronger version of the No Constraint Principle he ascribes to the received view – that is, a thesis proscribing methodological *and* ontological constraint.

a non-causal variety of determination. And, as we have seen from our examination of a concrete scientific case, certain properties are realizers of other properties *only if* the powers of these properties together non-causally result in the powers of the realized property instance. There are other important features of realization relations, but just given the latter aspect we can see that there are very clear, and tight, constraints upon which types of property are such that their instances can together realize some other instance. And, as a result of this ontological point, there are strong reasons to expect that, under certain circumstances (such as having sufficiently well-confirmed theories to be used in such constraint), the nature of realization relations will ground inter-theoretic constraints between the disciplines studying realizer and realized properties.

For example, if one has a very well-confirmed theory of the nature of some realized property, i.e. an account of its individuating powers, then this theory can be used 'top-down' to guide and even constrain research about the realizers of this property given our other information about them. These realizers must together result in the known powers of the realized property, so one can exclude certain hypotheses about the realizers, or prioritize others, depending upon whether these hypotheses make claims about the realizers' powers that together allow them to non-causally result in the powers of the realized property. In the reverse direction, working 'bottom-up', if one has a well-confirmed account of the nature of the realizer properties of some realized property, then this constrains theories of the realized property in various ways. For instance, precise knowledge of the realizers' powers can exclude, or prioritize, certain hypotheses about the individuating powers of the realized property. How does this work? Such theories of the realized property's nature are, in part, plausible to the degree to which we can see that the powers the hypothesis accords to the realized property are such that they can non-

causally result from the powers attributed to the realizers by our well-confirmed account of the latter. (We should note that such 'bottom-up' and 'top-down' constraint is potentially very fluid, for example operating in both directions at the same time, and/or changing direction over time. However, we will put these widely noted points to the side here, since they are orthogonal to our main concerns).

These conclusions are perhaps startling to some. Nonetheless, we believe these abstract points ground a persuasive case that, under certain conditions, because the properties involved in realization relations ontologically determine each other there will, consequently, be a range of obvious inter-theoretic constraints between the disciplines studying realizer and realized properties. Furthermore, we have seen there is strong empirical evidence for HPMR. Our conclusion is thus that we presently ought to endorse the following thesis in the psychological and neurological sciences, as well as the special sciences generally:

> (c) The special sciences studying realizer and realized properties, under appropriate conditions (such as sufficient confirmation, etc.), will inter-theoretically constrain each other and hence may co-evolve, through a process of mutual fit and adjustment, in a variety of beneficial ways.

Obviously, the central thesis of the received view, in (a), posits multiple realization relations and hence we also contend that proponents of the received view ought to endorse thesis (c). The resulting position, combining both ontological, semantic and methodological claims, in theses (a), (b) *and* (c), is what we shall term 'Integrated Multiple Realization' – for it accepts that the ontological 'integration' involved in realization relations entails, under appropriate conditions (such as having sufficiently

well-confirmed theories to be used in such constraint), methodological 'integration' between the sciences studying realizer and realized properties.

Obviously, Integrated Multiple Realization is a very different picture of the special sciences than Ghostly Multiple Realization, but we contend that Integrated Multiple Realization is the position one *should* endorse if one accepts multiple realization and hence thesis (a). In the next section, we will further examine whether, or not, proponents of the received view actually endorse Integrated Multiple Realization. However, we first want to draw out the implication of our findings for the Methodological Argument against multiple realization. For we should note that we now have good reason to think that the No Constraint Principle is false – and we will shortly bolster this conclusion with detailed evidence from actual scientific practice. Contrary to the Principle, which claims that multiple realization precludes inter-theoretic constraint, we have see there are good reasons to believe that, under appropriate conditions, scientific realization relations entail inter-theoretic constraints between theories in the neurological and psychological sciences. The clear conclusion is that the No Constraint Principle is mistaken. And since critics, such as Bechtel and Mundale, and Shapiro, use the Principle as a key premise of their argument, we must consequently conclude that the Methodological Argument against multiple realization is unsound.

Given these findings, we can diagnose what has gone awry in recent debates over multiple realization. We were earlier puzzled by the fact that critics who deny the existence of multiple realization nonetheless endorse the main empirical evidence that apparently supports its existence. And we can now see why this odd situation came about. Through their focus upon the mistaken No Constraint Principle, recent critics such as Shapiro, or Bechtel and Mundale, have wrongly concluded from their plausible evidence

about inter-theoretic constraint in the neurological and psychological sciences that there can be no multiple realization, thus blinding themselves to the empirical evidence that apparently suffices to establish HPMR. Use of the No Constraint Principle has meant that recent critics have gone even more radically astray, for once we understand the nature of realization we see that it does not preclude inter-theoretic constraint, but actually entails it under the right conditions!

At this point, in order to clarify our key claims, and further support them with empirical evidence, we want to consider Brian Keeley (2000)'s critique of what he terms the 'Multiple Realization Thesis'. In fact, using the same type of evidence we have emphasized in Part 1, Keeley explicitly contends with regard to the ontological phenomenon of multiple realization that:

> The fact of multiple realization is seemingly unassailable in workaday science. We do not have to resort to wild, science fiction thought experiments concerning Martians or artificially intelligent computers to find it. In an almost trivial sense, different humans multiply realize the same psychological states. (Keeley (2000), pp.448-9)

We obviously agree with Keeley that the evidence is such that the multiple realization of human psychological properties by neural properties is so prevalent as to be almost mundane or trivial. But, since he endorses the empirical support for the ontological claim inherent in HPMR, what then does Keeley take himself to be attacking in the 'Multiple Realization Thesis'?

Keeley explains his target as follows:

> In his 1974 paper… Fodor argues from the multiple realizability of functionally defined generalizations to the theoretical independence of those sciences that

> make use of functionalist theories… For the sake of brevity, I will refer to this argument as the multiply realization thesis... (Keeley (2000), p.446)

Here by the 'Multiple Realization Thesis', Keeley is either referring directly to what we have termed the No Constraint Principle or, at least, to the Argument from Autonomy we have suggested that many, like Keeley, take Fodor and others to base upon the Principle.

To assess the plausibility of his target, Keeley then examines an interesting case of multiple realization from the sciences in the convergent evolution of jamming avoidance behaviors in electric fish. Keeley thus seeks to show that in this case the sciences studying heterogeneous realizers, and associated multiply realized properties, do in fact theoretically constrain each other in numerous ways. Consequently, Keeley argues that we should reject the No Constraint Principle, which he terms the 'Multiple Realization Thesis'. As a result, Keeley instead endorses a picture whose ontology encompasses the multiple realization of psychological properties by neural properties, but whose methodology acknowledges that there are inter-theoretic constraints between the sciences studying these heterogeneous realizers and multiply realized properties. Keeley thus concludes:

> …I am willing to live with a philosophy of science in which the special sciences have an equally important role to play as the structural sciences, but which grants neither a more primary role. That is the lesson taught by the neuroethology of electric fish. I leave it to the reader to judge how shocking this lesson is. (Keeley (2000), p. 463).

Obviously, we whole-heartedly endorse Keeley's findings. For they reinforce our more abstract conclusions about the implications of the metaphysics of realization for the methodology of the sciences studying realized and realizer properties. Keeley in effect

provides an elegant case-study in which evidence from scientific practice supports the truth of what we have termed Integrated Multiple Realization. However, Keeley's article is therefore a little shocking in its implications because this "critic" of multiple realization actually provides compelling scientific grounds for rejecting the No Constraint Principle and consequently *both* the Argument from Autonomy *and also* the Methodological Argument defended by other critics of multiple realization such as Shapiro, or Bechtel and Mundale.

To summarize, we have outlined abstract reasons to reject a key premise of the Methodological Argument in the No Constraint Principle. Furthermore, we have now seen that Keeley's work provides a nice template for the manner by which empirical evidence against the Principle can easily be garnered. Our conclusion is consequently that, far from being evidence against its existence, the examples of inter-theoretic constraint in the neurological and psychological sciences recently broached by critics is actually most plausibly viewed as one more manifestation of widespread multiple realization in these disciplines. For, given the empirical evidence we have seen supports HPMR, such constraint is just what Integrated Multiple Realization would predict one would find in cognitive science, psychology and the neurosciences.

Part 3 – What Was the Received View, Anyway?

Before examining the other main argument against multiple realization we want to briefly return to the exegetical issue we earlier put to one side: Do proponents of the received view really endorse the No Constraint Principle, use the Argument from Autonomy based upon it, and hence endorse the Ghostly Multiple Realization position that results? Obviously this is a large question given the numbers of philosophers who

have contributed to the defense of the received view and it will be most useful here to primarily examine what Jerry Fodor has written on this issue, since Fodor is most often associated by critics with the No Constraint Principle and claims of radical 'autonomy' for the psychological sciences.[14]

From the very beginning of his career, with his seminal book *Psychological Explanation* (Fodor (1968)), Fodor argued that multiple realization is common between neural and psychological properties and, more importantly, endorsed the point that the nature of these relations means that there will be, in principle, inter-theoretic constraints between the disciplines studying these properties. To illustrate this controversial point we want to examine a typical passage from *Psychological Explanation* where Fodor summarizes his account of the relations between the neurological and psychological sciences as follows:

> The two phases of psychological explanation thus condition one another. On the one hand, it is clear that a psychological theory that attributes to an organism a state or process that the organism has no physiological mechanisms capable of realizing is ipso facto incorrect. …
>
> On the other hand, the relevant notion of a neurological subsystem is that of a biochemical mechanism whose operation can correspond to some state or process that is postulated by a satisfactory psychological theory…
>
> The problem, then, is one of fit and mutual adjustment… adjustment of the psychological characterization of function to considerations of neurological plausibility, and vice versa. (Fodor (1968), pp.110-11)

[14] See, however, the discussion of Classical Mendelian genetics and DNA in Kitcher, (1984). Kitcher explores ways in which Mendel's second law might be refined, or constrained, by discoveries involving the DNA of chromosomes.

As this and other passages make plain, there is a plausible exegetical case that from the start of his work on special sciences Fodor rejected the No Constraint Principle and instead endorses a range of, in principle, inter-theoretic constraints between the neurological and psychological sciences. In fact, such passages suggest that when suitably mature theories are available in the neurological and psychological sciences Fodor defends the utility of a 'co-evolutionary research strategy' of just the type that critics of multiple realization also later endorsed (Churchland (1986)).[15]

It thus appears that Fodor explicitly endorses Integrated Multiple Realization, and theses (a), (b) *and* (c), rather than the Ghostly Multiple Realization picture so often recently ascribed to him. But how then did such a mistaken interpretation come about? We suggest we can identify a number of reasons. First, it should now be obvious that it is extremely damaging to lump together all proponents of multiple realization, or related doctrines such as 'functionalism'. Most particularly, we have seen that it is dangerous to assume that the views of Putnam, the initial popularizer of multiple realization, are shared by other defenders of multiple realization. Putnam's seminal arguments about the implications of multiple realization were driven primarily by thought experiments and Putnam was thus apparently led to implausible claims about the methodological implications of multiple realization. In contrast, defenders of the received view of special sciences, such as Fodor, Wimsatt and Kitcher, focused upon concrete scientific examples of multiple realization and more clearly saw the resulting methodological constraints that realization places upon the sciences studying realizer and realized properties.

A second reason why such mistaken readings of the received view become attractive is through failures to clarify, and disentangle, distinct theses. For example, a

[15] See Fodor (1968), chapter 3.

variety of complex, and subtly different, issues surround the quite different notions of 'autonomy' inherent in the No Constraint Principle and thesis (b) of the received view. The former denies there are any methodological constraints between neurological and psychological sciences, whereas the latter merely claims that we cannot dispense with psychological sciences and their predicates – where this crucially leaves open the possibility that psychological notions, however indispensable as a group, will be constrained by, and potentially co-evolve through interaction with, the findings and predicates of the neurological sciences. Rather than the Principle, writers like Fodor, Wimsatt and Kitcher plausibly only sought to defend (b), and the indispensability of special science predicates, in response to the Positivists' claims that, ultimately, special science predicates could all, in principle, be dispensed with in favor of the predicates of physics. Unless one is careful to unpack, and distinguish, these differing notions of 'autonomy', then it is all too easy to mistake acceptance of thesis (b) with an endorsement of the No Constraint Principle. Such confusion apparently partially underlies mistakes about the substance of the received view and its commitments.

Finally, the mistaken interpretations of the received view may also appear plausible if one fails to separate claims about *in practice*, as opposed to *in principle*, failures of inter-theoretic constraints between the neurological and psychological sciences. For instance, whether rightly or wrongly, Fodor has long questioned whether we *presently* have sufficiently developed, and hence well-confirmed, theories in the neurological sciences such that *in practice* the conditions are right for inter-theoretic constraint, and a full co-evolutionary research strategy, to be fruitfully pursued.[16] The critics' ascription of the No Constraint Principle to Fodor, and hence the received view,

[16] See, for example, Fodor & Pylyshyn, (1988), pp. 62-64.

may well be due, in part, to a mistaken reading of Fodor's claims about the failure of constraint between the neurological and psychological sciences *in practice,* given the present state of the neurosciences, as an endorsement of the stronger *in principle* claims of something like the No Constraint Principle.

We should finish this section by emphasizing that these exegetical issues have not been our primary focus and that we have not used any exegetical arguments as the support for our substantive conclusions. Regardless of whether proponents of the received view have in fact accepted such claims, we have shown that anyone who endorses multiple realization, and thesis (a), also *ought* to accept the existence of, in principle, inter-theoretic constraints between the neurological and psychological sciences and hence embrace thesis (c) as well. Nonetheless, we have shown that if one carefully examines his writings, then it appears that Fodor actually explicitly endorses a view very much like Integrated Multiple Realization and even the, in principle, utility of a co-evolutionary research strategy in the neurological and psychological sciences under appropriate conditions. The common interpretation of Fodor as endorsing the No Constraint Principle thus appears to be mistaken and similar points arguably hold for the other main proponents of the received view.[17]

Part 4 – Metaphysical Arguments and the Nature of Multiple Realization in the Neurological and Psychological Sciences.

[17] For example, Wimsatt's papers make a strong case that he endorses multiple realization, but also accepts there will consequently be inter-theoretic constraint between the sciences studying realizer and realized properties – in fact, Wimsatt arguably largely pioneered the very notion of a 'co-evolutionary research strategy'. (See Wimsatt (1974), (1976), and (1994), amongst others).

It would be remiss of us if we did not consider another very prominent class of more theoretical arguments against multiple realization that is found in the work of writers such as Shapiro and Jaegwon Kim. These are what we are terming 'Metaphysical Arguments' against the existence of scientifically legitimate properties that are multiply realized, since they rely upon a particular account of the metaphysics of realization relations in the sciences. For, in contrast to the Dimensioned account of realization implicitly endorsed by the received view, such Metaphysical Arguments use what has elsewhere been dubbed the 'Flat' view of realization (Gillett (2002)).

The Flat account has been defended by Jaegwon Kim (1998), Sydney Shoemaker (2001), and others, and comprises two inter-connected claims. The first concerns the individuals in which realizer/realized properties are instantiated and is framed thus:

> (F-I) A property instance X realizes a property instance Y *only if* X and Y are instantiated in the same individual.

The second feature distinctive of the Flat view, concerning the causal powers of realized/realizer properties, may be summarized in this thesis:

> (F-II) A property instance X realizes a property instance Y *only if* the causal powers individuative of the instance of Y match causal powers contributed by the instance of X (and where X may contribute powers not individuative of Y).

Through (F-I) and (F-II), the Flat view of realization earns it name by taking realized and realizer properties to share both the individual in which they are instantiated and at least some of the causal powers contributed to this individual.

Once the nature of the Flat view of realization is made explicit, then we can see how this account underpins the Metaphysical Arguments against multiple realization to be found in the work of Kim ((1992), (1998), (1999)), Shapiro ((2000), (2004)) and

Lenny Clapp (2001), amongst other writers. Here we will take Kim as our example in order to illuminate the nature, and problems, of such Metaphysical Arguments, since we have critically examined Shapiro and Clapp's reasoning elsewhere.

Kim has offered a very prominent Metaphysical Argument that seeks to show legitimate scientific properties cannot be multiply realized because properties that are multiply realized are such that the predicates referring to them are not projectible. Given our purposes, it is most instructive to consider the later summary that Kim gives of his argument, where he paraphrases "projectibility" of predicates as whether a property is able to "figure in a law". For instance, Kim tells us:

> If the "multiplicity" or "diversity" of realizers means anything, it must mean that these realizers are causally and nomologically diverse. Unless two realizers of E show significant causal/nomological diversity, there is no clear reason why we should count them as two, not one. It follows then that multiply realizable properties are ipso facto causally and nomologically heterogeneous… All this points to the inescapable conclusion that E, because of its causal/nomic heterogeneity, is unfit to figure in laws, and is thereby disqualified as a useful scientific property… (Kim (1999), pp.17-18)

Here we can see how Kim relies upon the Flat view in his claims about multiple realization and its implications for projectibility. For Kim's argument is driven by his adherence to condition (F-II) of the Flat view - that a realizer shares its powers with the property instance it realizes. And since the realizers of multiply realized properties are heterogeneous in their contributions of powers, Kim reasons, so too must the realized property instances be heterogeneous in their powers. Consequently, the E property instances referred to by the special science predicate will vary in their powers under the

same conditions. Properties that vary in their powers in this way do not behave uniformly. Predicates picking-out property instances that do not behave uniformly are not projectible. Therefore, a special science predicate that refers to a multiply realized property is not projectible and the property it refers to is not a fit scientific property – it will not be a property that figures in true law-like statements, for example. We will call this 'Kim's Metaphysical Argument' against the multiple realization of scientifically legitimate properties.

Unfortunately, as we have seen already, in Part 1, prominent proponents of the received view of special sciences arguably endorse the Dimensioned view of the metaphysics of realization. And under this alternative view of realization no such inferences as those embodied in Kim's Metaphysical Argument go through. For, as we earlier noted, under the Dimensioned account we have a wider notion of causal role-playing where properties can realize other property instances *without* contributing any common powers. Thus we cannot simply assume that because realizers are heterogeneous in their contributions of powers, then these realizers will result in different powers. For the heterogeneous realizer property instances can together all result in the *very same* powers, i.e. the powers of the realized property, albeit through contributions of distinct powers. We saw earlier by examining a concrete case from the special sciences, involving properties of distinct individuals, that this is very often the case. As a result, we get no swift argument from the heterogeneity of realizers to differences in the powers of realized properties, or to the lack of uniformity of the powers of multiply realized properties, or to the unprojectibility of special science predicates picking-out multiply realized properties. Furthermore, we have no reason to think that special science predicates cannot figure in true law-like generalizations.

In fact, the Dimensioned account of realization illuminates *how* multiply realized properties are projectible despite being realized by heterogeneous realizer properties and relations. The deeper point thrown into abstract relief by this metaphysical account is that very different properties and relations can contribute wholly distinct powers that *together* non-causally result in the powers of the realized property instance. As a result, we can see how very different realizer properties may underwrite the projectibility of the same special science predicate. And, as yet, Kim has provided no reasons to favor the Flat view of realization over the Dimensioned account. Given the fact that Kim's arguments against projectibility do not go through under the Dimensioned view, and that his opponents accept this alternative view of realization which supports the projectibility of special science predicates, we are led to conclude that Kim's Metaphysical Argument against the multiple realization of scientifically legitimate properties is presently at least question-begging. And, in this respect, Kim's reasoning mirrors versions of the Metaphysical Argument against multiple realization recently offered by Shapiro and Clapp.[18]

One possible response that would protect the Metaphysical Argument from our objections would be to show that the Flat view should be preferred to the Dimensioned theory as an account of the realization in the sciences. However, we can now quickly see that exactly the reverse conclusion seems plausible: the Flat view fails to accommodate the evidence about properties in the neurological and psychological sciences, whereas the Dimensioned account effectively covers such scientific cases.[19] Our earlier example of the ion channel illustrates the problems and is typical of mechanism-based examples in

[18] See Gillett (2003) for a critique of the claims of Shapiro (2000), and also Clapp (2001), which are each shown to mirror Kim's Metaphysical Argument in being question-begging through their reliance upon the Flat view. And see Gillett (Forthcoming) for an extension of such criticisms to Shapiro (2004).
[19] These points are defended at more length in Gillett (2002).

the special sciences. The Flat view of realization cannot count the compositional relations between properties in such cases as realization relations. First, the properties of the protein sub-units fail (F-I) because they are instantiated in the protein subunits and not the ion channel which is the individual instantiating the realized property. And, second, the properties of the protein sub-units also fail (F-II) because they overlap in none of their powers with the relevant property of the ion channel. However, it appears that the properties of the proteins realize the property of the ion channel. For, as we have seen, the former properties non-causally result in the latter property because the powers they contribute together non-causally result in the powers individuative of the properties of the ion channel.

Given the latter points, we suggest that the ion channel example, and all the other cases involving implementing mechanisms in the special sciences, show that the Flat view should be rejected as an account of scientific realization. In contrast to these failings, we have already seen, in Part 1, that the Dimensioned view provides an illuminating account of such realization and is thus more plausible than the Flat view. As a result, we conclude that the Metaphysical Arguments against multiple realization, grounded upon the Flat account, are plausibly unsound, as well as question-begging.

Let us conclude by looking more widely, for we have seen that the philosophers who oppose multiple realization are united by a number of common commitments. The erstwhile target of many writers in this ‘camp’ is the received view of special sciences, though critics usually interpret the received view as endorsing Ghostly Multiple Realization. In addition, the members of this movement have all rightly championed the importance of methodological constraints, and other interactions, between the psychological and neurological sciences, evidence which we have seen that they deploy

in the Methodological Argument against multiple realization. And such writers have also endorsed the Flat view of realization which they also use to attack the existence of scientifically legitimate multiply realized properties through Metaphysical Arguments. Often these critiques of multiple realization have been conjoined with, or even used as launching pads for, defenses of identities between psychological and neural properties.[20] And many of the writers in this 'camp' have also consequently defended various forms of 'reduction' that imply the, in principle, dispensability of psychological predicates and sciences.

In response to the arguments of this nascent tradition, we have shown that realization, whether multiple or otherwise, actually generates obvious inter-theoretic constraints, under the appropriate conditions, between the sciences studying realizer and realized properties. We thus agree with recent critics that the Ghostly Multiple Realization view of the special sciences should be consigned to the intellectual scrap-heap. But our broader finding was that there are clear reasons to think that abandoning Ghostly Multiple Realization neither suffices to establish that multiple realization does not exist, nor even that the received view of special sciences should be abandoned. For we established that the Metaphysical Arguments against multiple realization are either question-begging, unsound, or both. And we further showed that methodological evidence from the sciences, marshaled by recent critics, is either compatible with, or even further confirms, the existence of multiple realization, rather than undermining it.

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[20] For example, Kim (1998) and (1999) uses the Flat view of realization in order to defend identities between realized and realizer properties. Whilst Bechtel and Mundale (1999) suggest that their critique of multiple realization may support identities – presumably their idea is that if multiple realization blocked identities, then once the existence of multiple realization is undermined such identities are back in play.

Furthermore, we highlighted the range of empirical evidence presently supporting HPMR and widespread multiple realization in the psychological and neurological sciences.

Our foregoing arguments have consequently provided reasons to accept a view of the ontology, and methodology, of the special sciences that endorses the existence of multiple realization, in thesis (a), and the importance of inter-theoretic constraint between disciplines studying realized and realizer properties, in claim (c). Such a position is perfectly compatible with accepting the indispensability of psychological predicates and sciences, and acceptance of claim (b), since the latter thesis allows psychological predicates may be molded and constrained by the notions of the neurological sciences, and vice versa. And, as we briefly outlined, exegetical evidence shows that defenders of the received view in fact endorse the resulting Integrated, rather than Ghostly, Multiple Realization view of the special sciences. Perhaps most importantly, our final conclusion is consequently that Integrated Multiple Realization, combining theses (a), (b) *and* (c), is presently the most adequate account of the special sciences in general and, given the empirical evidence supporting HPMR, of the psychological and neurological sciences in particular.[21]

[21] Acknowledgements removed for refereeing.

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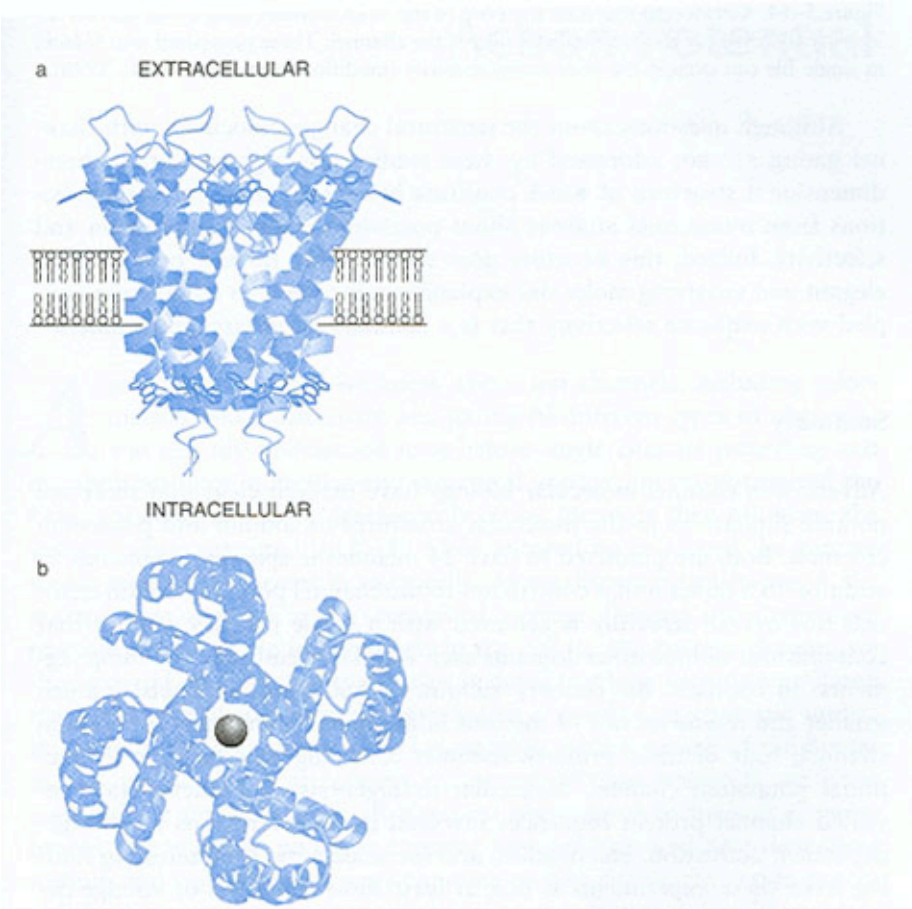

Figure 5–13. Ribbon diagrams to illustrate the three-dimensional structure of the KcsA potassium channel that was solved by Rod MacKinnon and colleagues. *a*: View from the side. Note the "inverted teepee" shape. *b*: View looking down on the entry to the channel from the extracellular side. A potassium ion (*black*) is shown in the central pore formed by the fourfold symmetrical protein (*blue*). See also Plate 5. (Modified from Doyle et al., 1998.)

Figure 1

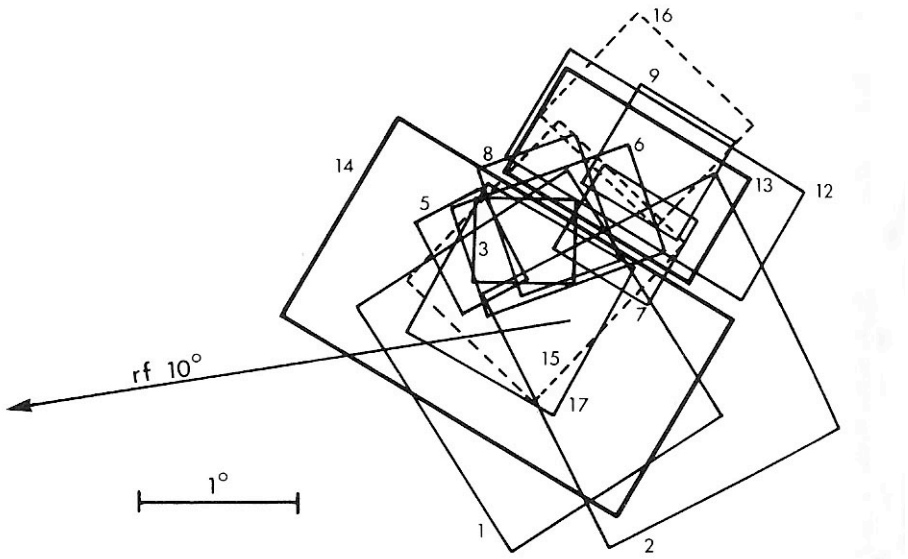

Fig. 1. Scatter of receptive fields in a perpendicular penetration. Receptive-field positions of 14 consecutively recorded cells from monkey striate cortex 10 mm to the left of the midline and 15 mm behind the lunate sulcus. The fields, mapped in the right eye, were 10° from the right fovea, just above the horizontal meridian. Fields 13 and 14 (heavy lines) are mapped for simultaneously recorded cells, as are fields 15 and 16 (interrupted lines). Eye positions are monitored with a reference electrode in the left striate cortex by repeatedly checking receptive-field positions of a binocular cell. The scatter, relative to the receptive-field size, is typical for area 17.

Figure 2

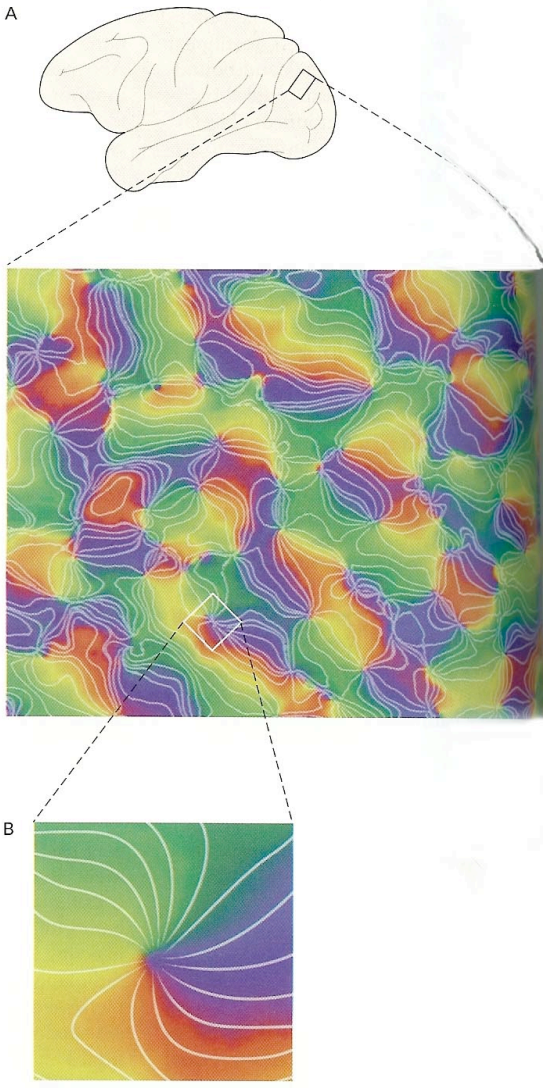

Figure 27-14 Orientation columns in the visual cortex of the monkey. (Courtesy of Gary Blasdel.)

A. Image of a 9 by 12 mm rectangle of cortical surface taken while the monkey viewed contours of different orientations (indicated on the right). This image was obtained through optical imaging and by comparing local changes in reflectance, which indicate activity. Areas that were most active during the presentation of a particular orientation are indicated by the color chosen to represent that orientation (bars on the right). Complementary colors were chosen to represent orthogonal orientations. Hence, red and green indicate maximal activities in response to horizontal and vertical, while blue and yellow indicate greatest activation by left and right oblique.

B. Enlargement of a pinwheel-like area in A. Orientations producing the greatest activity remain constant along radials, extending outward from a center, but change continuously (through ± 180°).

Figure 3

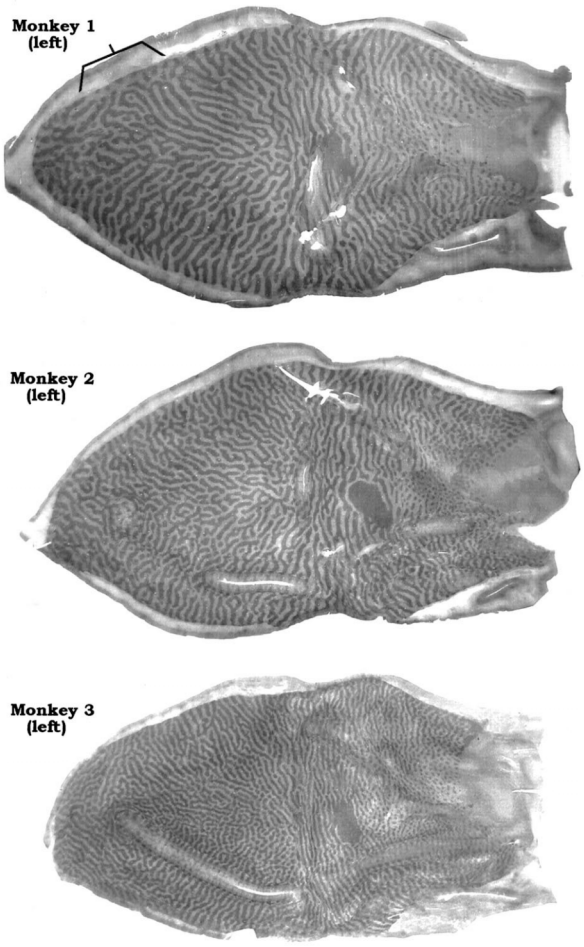

Figure 4