

# The representational–hierarchical view of pattern separation: Not just hippocampus, not just space, not just memory?



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## ARTICLE INFO

### Article history:

Received 6 October 2015

Revised 6 January 2016

Accepted 13 January 2016

Available online 1 February 2016

### Keywords:

Pattern separation

Memory

Hippocampus

Perirhinal cortex

Representational–hierarchical

Perception

## ABSTRACT

Pattern separation (PS) has been defined as a process of reducing overlap between similar input patterns to minimize interference amongst stored representations. The present article describes this putative PS process from the “representational–hierarchical” perspective (R–H), which uses a hierarchical continuum instead of a cognitive modular processing framework to describe the organization of the ventral visual perirhinal–hippocampal processing stream. Instead of trying to map psychological constructs onto anatomical modules in the brain, the R–H model suggests that the function of brain regions depends upon what representations they contain. We begin by discussing a main principle of the R–H framework, the resolution of “ambiguity” of lower level representations via the formation of unique conjunctive representations in higher level areas, and how this process is remarkably similar to definitions of PS. Work from several species and experimental approaches suggest that this principle of resolution of ambiguity via conjunctive representations has considerable explanatory power, leads to wide possibilities for experimentation, and also supports some perhaps surprising conclusions.

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## 1. Introduction

The importance of complex conjunctive representations for the resolution of ambiguity in lower-level representations has been a major focus of our research and that of others. Much work from several species and experimental approaches suggests that this principle of resolution of ambiguity via conjunctive representations has considerable explanatory power, particularly regarding how best to understand the effects of focal brain dysfunction (e.g., Barense et al., 2005, 2012; Bartko, Winters, Cowell, Saksida, & Bussey, 2007; Bussey & Saksida, 2002; Cowell, Bussey, & Saksida, 2006; Cowell, Bussey, & Saksida, 2010a; Graham et al., 2006; Lee, Buckley, et al., 2005; Lee, Bussey, et al., 2005; Lee & Rudebeck, 2010; McTighe, Cowell, Winters, Bussey, & Saksida, 2010). We have referred to this way of thinking about brain organization as the “representational–hierarchical” perspective (R–H) (e.g., Bussey & Saksida, 2002, 2005; Murray, Bussey, & Saksida, 2007; Saksida & Bussey, 2010).

Recently there has been a great deal of interest in a process referred to as “Pattern Separation” (PS). PS has been defined as “... reducing interference among similar inputs by using non-overlapping representations...” (e.g., Reagh et al., 2014) and “...the ability of the network to reduce the overlap between similar input patterns before they are stored in order to reduce the probability of interference...” (Neunuebel & Knierim, 2014). Clearly the main principle of the R–H framework, the resolution of the “ambiguity” of lower level representations via the formation of unique conjunctive representations in higher level areas, is a strikingly similar idea to the above conceptions of PS. The present article is, therefore, aimed at researchers interested in PS, and explores the question: To the extent that researchers are interested in PS because it results in the formation of new, interference-reducing representations, what insights into PS might be offered by considering some of the conclusions resulting from R–H theory?

A quick word about the scope and aims of this review. R–H theory grew out of an interest in the *functional relevance* of processes and representational content in the brain. That is, what such processes and representational content do for us, in aspects of cognition such as memory and perception. The way to determine this is through empirical, causal behavioral experiments that measure

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cognition. Non-empirical approaches such as computational modeling have been hugely important in the area of PS (O'Reilly and McClelland, 1994; Rolls, 1987, 1989, 1990; Norman & O'Reilly, 2003; Rolls & Kesner, 2006; Treves & Rolls, 1994) and indeed, experiments testing the R–H view have been guided by computational modeling (e.g., Barense et al., 2012; Bartko et al., 2007; Cowell et al., 2006). But we must remember that these are models, and at some point experiments on real brains must be done. Correlational experimental approaches, particularly electrophysiology, have shed much light on PS at the cellular and network levels (e.g., Neunuebel & Knierim, 2014; Knierim & Neunuebel, 2016), and focus on PS as a specific mechanism involving the transformation of an input representation to an output representation, in which the output is less correlated than the input (in line with computational models). However this process is of interest because of the representations thus formed and in particular their requirement for cognition (usually memory). Correlational approaches generally do not address this requirement. Additionally, correlational approaches have largely focussed on the hippocampus, whereas a main aim of what follows below is a suggestion that we need to consider other areas of the brain with respect to PS. Fully understanding any function of the brain cannot be accomplished by any single method alone, but requires converging, complementary approaches.

Furthermore, our focus in this article is the relevance to cognition of the *result* of processes such as PS, i.e., the representations that are formed from such processes. We will not, in this review, discuss *how* these representations are formed. For example, we will consider that such representations may be housed in the ventral visual stream, but not the way the formation of such representations might be related to the receptive fields of neurons. Comprehensive treatments of such issues, along with the properties of such representations (e.g., invariance), can be found in other sources such as Rolls (2016).

Insofar as PS can be considered to be a process of forming new representations that help resolve ambiguity, the results of experiments carried out under the auspices of R–H theory lead us to offer a number of possibly surprising hypotheses about PS, including:

1. PS is fundamental to many aspects of cognition including perception; it is not just for memory.
2. PS happens in many cortical regions, not just the hippocampus.
3. PS happens for all stimulus material and not just 'spatial' or 'episodic' material. It happens for different types of representations, in the different regions and different levels throughout the "representational hierarchy".
4. The dentate gyrus (DG) is unlikely to maintain all levels of representation, and thus is not a truly domain-general pattern separator.
5. PS – insofar as this term equates with the formation of interference-reducing conjunctive representations – may have much wider explanatory power for understanding the effects of brain dysfunction than previously suspected.

Below we provide a brief history and summary of R–H theory, with special emphasis on these particular conclusions regarding PS, and then return to these points.

## 2. The Representational–Hierarchical model: A brief history and summary

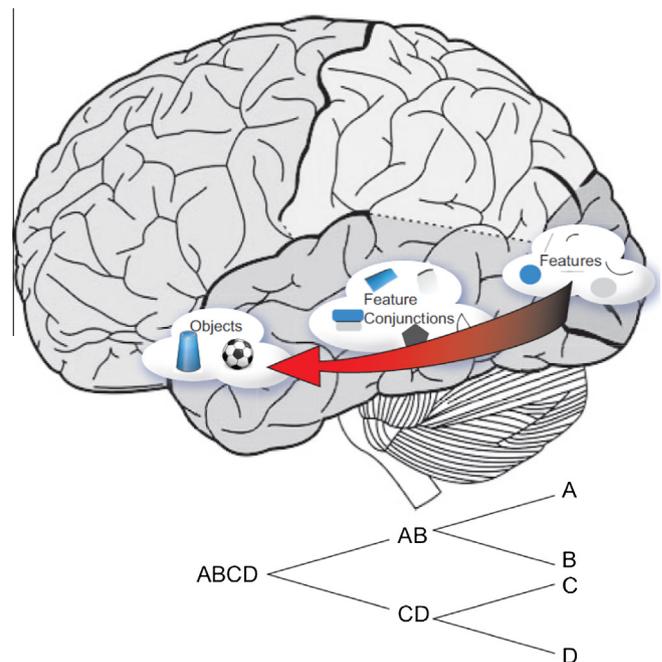
The R–H view was first presented in 1998 (Saksida & Bussey, 1998) and discussed in a review article in 1999 (Murray & Bussey, 1999). Eventually the first modeling and experimental studies testing the theory were published (Bussey & Saksida, 2002; Bussey, Saksida, & Murray, 2002, 2003). Although R–H takes a broad view of cognition, initial studies focused on visual cognition, and in

particular the issue of whether there are dedicated, anatomically segregated memory (Squire & Zola-Morgan, 1991) and perceptual representation (Schacter & Tulving, 1994) systems in the brain. Initial experimental studies focused on perirhinal cortex (PRh) as a "testing ground" at the anatomical interface between putative memory and perceptual systems. Other authors published similar ideas (e.g., Buckley & Gaffan, 1998; Gaffan, 2002) around this time and since (e.g., Graham, Barense, & Lee, 2010; Nadel & Peterson, 2013).

Our approach was to try to understand impairments in visual cognition following focal brain dysfunction. The prevailing view was that such impairments could be understood in terms of damage to a processing module specialized for a particular aspect of cognition (Schacter & Tulving, 1994; Squire & Zola-Morgan, 1991). In contrast to such a modular view, R–H theory proposed that representations are organized in a hierarchical continuum and are useful for all aspects of cognition that require them, including memory and perceptual discrimination [indeed we initially referred to this idea as the "Perceptual-Mnemonic/Feature-Conjunction" model (Bussey & Saksida, 2002)]. Thus, R–H emphasizes *content* rather than processing. The strongest version of the view is that there are no substantive processing differences within these various regions, and effects of brain dysfunction can be understood entirely on the basis of content (see Forwood, Cowell, Bussey, & Saksida, 2012). Although this very strong version of the view is unlikely to be entirely correct, it is perhaps surprising just how much it has been able to explain, without having to invoke putative differences in processing.

The basic idea of the R–H view is illustrated in Fig. 1.

To summarize a few key principles of R–H theory:



**Fig. 1.** R–H applied to visual cognition (adapted from McTighe et al., 2010). As representations pass through regions of the visual ventral stream (VVS) and into the medial temporal lobe, they become increasingly more complex in a hierarchical fashion. Representations supported by caudal regions represent "features" (e.g. A, B, C and D), whilst representations supported by more rostral regions represent conjunctions of those features (eventually leading to a representation at the level of a whole object-level representation (ABCD) in PRh and spatial and contextual representations in the hippocampus). The traditional multiple memory systems view suggests that structures within the medial temporal lobe subserve exclusively (declarative) mnemonic function, whereas structures in the ventral visual stream are important for functions such as perceptual discrimination. In contrast, the representational–hierarchical view suggests that stimulus representations throughout the ventral visual–perirhinal–hippocampal stream are useful for any cognitive function that requires them.

1. R–H emphasizes content, rather than process.
2. R–H assumes there is no ‘configural’ or ‘conjunctive’ region of the brain; each area contains conjunctive representations at different levels of complexity.
3. These conjunctive representations have the property that “the whole is greater than the sum of the parts” (see Baker, Behrmann, & Olson, 2002; Desimone, Albright, Gross, & Bruce, 1984; Erez, Cusack, Kendall, & Barense, 2015; Gross, 2008; cf Sripati & Olson, 2010).
4. Lesions in particular brain regions disrupt performance on tasks for which the representation contained within the region are useful – irrespective of what putative cognitive processing function has been used to label the task. These labels for tasks usually come out of the implicit or explicit assumption of processing modules, which the tasks are designed to tap. R–H proposes that there are no such modules.
5. Higher-level conjunctive representations help to disambiguate the behavioral significance of lower-level representations. But rather, lower-level representations of individual visual features are likely to occur across many objects or situations. Each of these features is therefore likely to be associated with different outcomes when part of different objects or events, creating ambiguity. Higher-level, more unique conjunctive representations are less likely to occur across many objects or events and can therefore help to disambiguate the individual features.

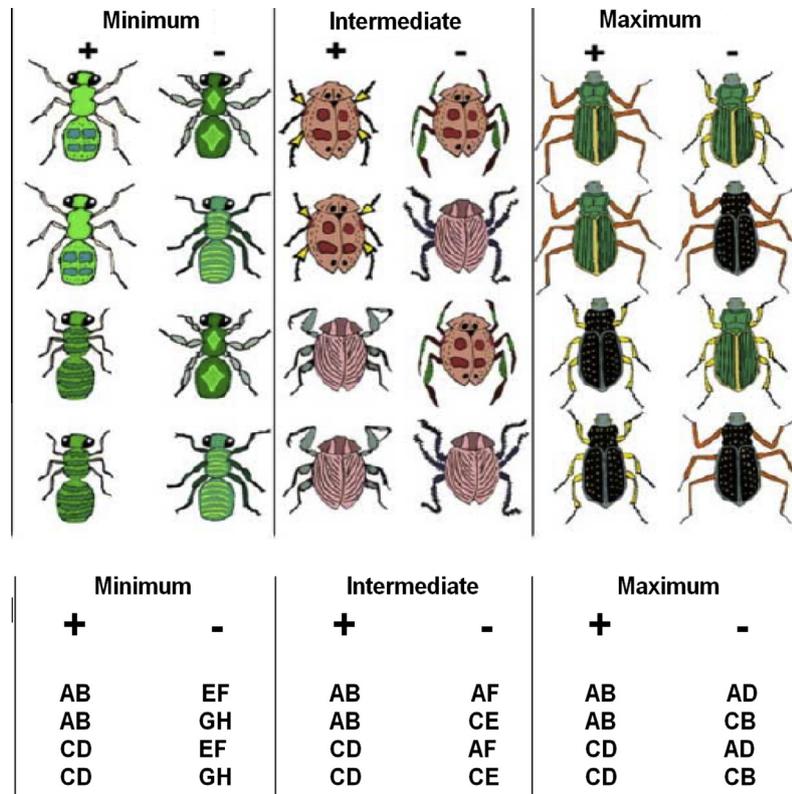
This last point is critical for explaining the effects of brain dysfunction on cognition, and where the concept of PS might fit into R–H theory. To illustrate, let’s use our early experiments on the PRh. Following the standard model of VVS organization (Desimone & Ungerleider, 1989; Riesenhuber & Poggio, 1999; Tanaka, 1996), we assumed that the PRh holds object-level representations, whereas feature-level representations are held in more caudal regions of the stream (Bussey & Saksida, 2002). The model further assumed a high degree of specificity of the representations in PRh (the idea that ‘the whole is greater than the sum of the parts’), an assumption that has now been supported by electrophysiological and imaging studies (Baker et al., 2002; Erez et al., 2015). Indeed, other studies have since confirmed the existence of highly specific complex visual representations throughout the MTL (Quiroga, Kreiman, Koch, & Fried, 2008; Quiroga, Reddy, Kreiman, Koch, & Fried, 2005). These specific complex conjunctive representations prevent the subject from having to rely only on simple feature representations (i.e., isolated parts of stimuli) in upstream areas when solving tasks such as visual discriminations. This is important when individual features are not sufficient to solve a problem. For example, subjects with damage in PRh are impaired on tasks when features reoccur in both rewarded and non-rewarded objects. Thus complex conjunctive representations resolve feature ambiguity in lower-level representations – a concept strikingly similar to the notion of PS as “...reducing interference among similar inputs by using non-overlapping representations...” (e.g., Reagh et al., 2014)

We and others have used many different tasks to manipulate feature ambiguity (and thereby the requirement for PS), including versions of the biconditional discrimination (Barense et al., 2005; Bartko et al., 2007; Bussey et al., 2002) and morphing stimuli together to increase similarity (Barense et al., 2005; Bartko et al., 2007; Bussey et al., 2002). Fig. 2 depicts three conditions of a concurrent pair-wise discrimination task as an example of the use of biconditional discrimination and its variants to manipulate feature ambiguity. Each set of discriminations show bugs comprised of two features: legs and body plan (represented in Fig. 2 using a distinct letter for each feature). When ambiguity is minimal (left column), the discrimination can be solved based on a single feature alone. For example, body plan A is always correct, whilst body plan

E is never correct. This is true of all individual body plans and leg configurations. When there is maximum ambiguity (right column), all individual features are rewarded equally often, but conjunctions of those features are selectively rewarded. For example, body plan A is rewarded when paired with leg configuration B but not with leg configuration D, whilst body plan C is rewarded when presented with leg configuration D, but not when in combination with leg configuration B. However, the combination of body plan A and leg configuration B is always rewarded, whilst the conjunction of body plan A and leg configuration D is never rewarded. Importantly, the combination of individual features into a conjunctive representation is necessary to solve the task in the maximum, but not the minimum ambiguity condition.

In addition to these initial explorations, the same basic principles have been used to explain a number of phenomena; for example:

1. *Impairment in pair-wise visual discriminations following PRh damage.* The seemingly contradictory findings that some pair-wise visual discriminations are impaired following damage to PRh whereas others are not, can be explained in terms of feature ambiguity (Bussey & Saksida, 2002; Barense et al., 2005; Bussey et al., 2003). Pairwise discriminations that are highly ambiguous are impaired after PRh damage but if the discrimination can be solved on the basis of individual features alone then they are not. These experiments and others showed that damage to a structure that is part of the putative ‘medial temporal lobe declarative memory system’ (Squire & Zola-Morgan, 1991) could impair performance on tasks with no overt declarative mnemonic component, indicating that the prevailing view of non-overlapping memory versus perceptual representations systems could not be correct (e.g., Barense et al., 2005, 2012; Bartko et al., 2007; Bussey & Saksida, 2002; Cowell et al., 2006, 2010a; Graham et al., 2006; Lee, Bussey, et al., 2005; Lee & Rudebeck, 2010; McTighe et al., 2010).
2. *Increased susceptibility to interference following PRh damage.* The model predicted that disruption of the representations of high-level conjunctive representations in PRh would lead the system to be highly susceptible to interference from lower-level feature representations. This was confirmed experimentally in rats by Bartko, Cowell, Winters, Bussey, and Saksida (2010) and later shown in humans with amnesia by Barense et al. (2012).
3. *Delay-dependent impairments following PRh damage.* The model produces delay-dependent forgetting as a result of interference from stimulus input during the delay in a memory task. For example, delay-dependent impairments after PRh damage result from the lack of conjunctive representations to resolve the ambiguity of the simpler representations of lower-level regions that are more likely to be encountered during the delay (Cowell et al., 2006).
4. *False recognition following PRh damage.* The above mechanism made the counterintuitive prediction that impairment in object recognition after PRh dysfunction may not be due to forgetting *per se*, but to false recognition (due to interference), which was confirmed experimentally (McTighe et al., 2010) and later observed in AD mice and aged rats (Burke, Wallace, Nematollahi, Uprety, & Barnes, 2010; Romberg et al., 2012) and humans (Yeung, Ryan, Cowell, & Barense, 2013).
5. *Amnesia may best be understood as a deficit of encoding, consolidation and retrieval.* There is a classic debate over whether the primary deficit in amnesia is one of encoding (i.e., conversion of incoming information into a representation in the brain), storage/consolidation, or retrieval (i.e., the ability to access previously stored information; Butters & Cermak, 1980; Kopelman, 2002; Meudell & Mayes, 1982; Warrington & Weiskrantz, 1970). R–H suggests that brain damage can, at least with



**Fig. 2.** Concurrent object discrimination (adapted from [Barense et al., 2005](#)) in which each stimulus (bug) contains two types of features (legs and body plan). The ambiguity level can be manipulated by varying the degree to which the discrimination can be solved using single features alone (e.g. always choose A [body plan with four dots] or C [body plan with thick stripes] in the minimum condition) or requires the use of combinations of features (e.g. always choose AB [body plan with four spots and orange legs] or CD [black body plan and yellow legs] in the maximum ambiguity condition). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respect to object recognition, affect all three ([Bartko et al., 2010](#); [Saksida & Bussey, 2010](#)). An object, once encoded, is represented throughout the VVS. However, damage to medial temporal lobe regions such as PRh, as occurs in amnesia, affects only part of the representation of that object. Thus, although the complex conjunctive representation of the object is compromised, lower-level representations of the individual features that make up the object remain intact. Damage in rostral regions therefore affect both encoding and storage because the complex stimulus representations, normally maintained in rostral regions and that are important for the resolution of interference, cannot be formed or stored. Retrieval is also affected because there is competition between the remaining feature representations when individual features are shared between interfering and novel stimuli. Consistent with this interpretation, temporary dysfunction of PRh impairs object recognition during encoding (study phase), storage/consolidation (delay phase), or retrieval (test phase) ([Winters, Bartko, Saksida, & Bussey, 2007](#); [Winters & Bussey, 2005](#)), and similar findings have been reported in hippocampus ([Riedel et al., 1999](#)). Note this account diverges sharply from the usual approach, which is to understand amnesia as due to damage to a processing module specialized for a specific type of cognition (memory).

6. *Double dissociations of brain lesions do not force an explanation in terms of modularity.* An extended version of the model showed that the double dissociations in monkeys' visual discrimination performance following lesions to different regions of the visual hierarchy—usually interpreted as evidence for the modularity of

visual perception and visual memory—could be accounted for by compromised representations within a hierarchical representational continuum rather than impairment in a specific type of learning, memory, or perception ([Cowell et al., 2010a](#); also see [Plaut, 1995](#)).

7. *The representational hierarchy extends at least as far as the DG of the hippocampus.* The hippocampus is thought to contain higher-level representations than those in PRh, consistent with relational, cognitive map, or episodic views of hippocampus function, and thus might be thought of as the apex of the representational hierarchy we are considering ([Cohen & Eichenbaum, 1993](#); [O'Keefe and Nadel, 1978](#)). Although our work has not yet extended to the entorhinal cortex (EC), it seems reasonable to speculate that EC supports intermediate-level representations given its anatomical position connecting the PRh to the hippocampus (i.e. that it maintains representations that are of greater complexity than those of PRh, but of lower complexity than those of the hippocampus). This is supported by recent electrophysiological evidence indicating that lateral EC supports the processing of information about individual objects and locations based on a local reference frame (i.e. spatial cues in close physical proximity to the individual), whilst the grid-cell populated medial EC supports global (distal spatial cues) reference frames ([Neunuebel, Yoganarasimha, Rao, & Knierim, 2013](#)). Consistent with the non-modular nature of R–H, the hippocampus was shown to be involved in perceptual discriminations ([Lee, Bussey, et al., 2005](#); [Lee, Levi, Davies, Hodges, & Graham, 2007](#); [Lee, Scahill, & Graham, 2008](#); [Lee et al., 2006](#)) and other “non-declarative” tasks ([Chun & Phelps, 1999](#);

Graham et al., 2006), as long as the representation required for the task was higher-level, at the level of places or contexts. We explained how this view can account for the effects of hippocampus lesions on “recency memory” in terms of the resolution of *object* ambiguity by higher-level hippocampal representations – without having to assume the hippocampus is a module specialized for processing “recency memory” (Cowell et al., 2006). Furthermore, we have suggested that evidence taken to support the existence of “familiarity” or “recollection” processing modules in the PRh and hippocampus, respectively, may be equally compatible with the R–H content-based view (Cowell, Bussey, & Saksida, 2010b).

### 3. What does any of this have to do with PS?

The relevance of R–H principles to PS is that all of the above and more can be explained by the formation of highly discriminable representations that resolve interference or ambiguity, which is thought to be the function of PS (see definitions above). This suggests that PS is a rather powerful process that happens in many parts of the brain, and may be a major player in many aspects of cognition.

It is worth taking a moment to focus on the last point above, the proposal that the hippocampus is an equal partner with other structures within the representational hierarchy, in which all structures perform PS. Although the role of many different structures in PS has been emphasized by Kesner and his colleagues (e.g., Gilbert & Kesner, 2002, 2003; Gilbert, Kesner, & Lee, 2001; Hunsaker & Kesner, 2013), most computational theories have tended to emphasize the hippocampus—and particularly the DG—in PS (e.g., Norman & O’Reilly, 2003; Rolls, 1989, 1990; Treves & Rolls, 1994). After Marr (1971), these models usually regard the CA3 region of the hippocampus as an auto-associator that can retrieve full memories from partial cues, thereby making it essential for retrieval of episodic memories. According to these models, to operate efficiently and avoid interference, auto-associators require non-overlapping inputs. Because of its various physiological and anatomical properties, the prime candidate for a region that could reduce the overlap in inputs to CA3 is DG. However, rather than assuming that DG is but one region that may contribute to PS of inputs to CA3, these theories often make the assumption or claim that the hippocampus implements PS whereas the cortex does not (Norman, 2010; Norman & O’Reilly, 2003) or indeed that PS is the fundamental key to understanding the differences in the roles of the hippocampus versus the cortex in memory (Rolls, 2015). As a consequence, the vast majority of the work on PS is focused on the hippocampus. Furthermore, a particular population of hippocampal neurons – the immature adult-born neurons in DG – has been repeatedly implicated in PS (Bakker, Kirwan, Miller, & Stark, 2008; Bekinschtein et al., 2014; Clelland et al., 2009; Creer, Romberg, Saksida, van Praag, & Bussey, 2010; Gilbert et al., 2001; Hunsaker, Rosenberg, & Kesner, 2008; Kheirbek, Tannenholz, & Hen, 2012; Lee & Solivan, 2010; Leutgeb, Leutgeb, Moser, & Moser, 2007; McHugh et al., 2007; Nakashiba et al., 2012; Neunuebel & Knierim, 2014; Sahay et al., 2011; Tronel et al., 2012). Such findings have led to the suggestion that the DG is a universal pattern separator that is ‘domain agnostic’ (Azab, Stark, & Stark, 2014; Yassa & Stark, 2011). However these authors also acknowledge the evidence outlined above that PS happens in many brain regions and for many cognitive processes, for example in PRh at the level of objects. What is not clear to us is how the same inputs—e.g., objects—could be separated *twice*, once in, say, PRh and then again in the hippocampus. This needs to be explained. Furthermore, tasks such as those described above designed to test the necessity of ‘pattern-separated’ conjunctive *object* representations in PRh are completely unaffected, or even

enhanced, by hippocampus lesions (Kesner, Taylor, Hoge, & Andy, 2015; Saksida, Bussey, Buckmaster, & Murray, 2006, 2007), showing that DG cannot be a domain-general pattern separator.

Furthermore these authors and others discuss DG-mediated PS as being exclusively for memory. As we have seen, however, ‘pattern-separated’ object-level representations in PRh are not only important for memory; they are important for perceptual discrimination, amongst other functions. The view that PS must be ‘for’ a particular cognitive function follows from the (we believe incorrect) assumption of cognitive modularity. If one assumes that brain regions are specialized cognitive processing modules, then the PS that happens there must be ‘for’ that cognitive function and no other. Thus if one thinks the hippocampus is specialized for memory, then PS in the DG must be for memory. The R–H view is non-modular, and under this view PS can be for any cognitive process, not just memory.

Finally, we note that the apparent involvement of adult-born neurons in the DG in PS presents a challenge to the present view, namely: if PS happens in many regions where there is no neurogenesis, why are these new neurons necessary for PS only in the DG? One possibility is that complex, information-rich representations in the hippocampus, which in the case of episodic memory or one-trial contextual learning must be learned extremely rapidly, require the ultra-responsive, highly plastic new neurons in DG. But this idea is speculative. Furthermore, you may have noticed that we are now suggesting the possibility of different *processing* in one specific region of the hierarchy. Perhaps this is where the strong version of R–H, which claims that all can be explained by content without invoking differences in process, breaks down.

### 4. Concluding thoughts

To recap, the main points arising from this analysis are:

1. PS is fundamental to many aspects of cognition including perception; it is not just for memory.
2. PS happens in many cortical regions, not just the hippocampus.
3. PS happens for all stimulus material and not just ‘spatial’ or ‘episodic’ material. It happens for different types of representations, in the different regions and different levels throughout the hierarchy.
4. The DG is unlikely to maintain all levels of representation, so is not a domain-general pattern separator.
5. PS – insofar as this term equates with the formation of interference-reducing conjunctive representations – may have much wider explanatory power for understanding the effects of brain dysfunction than previously suspected.

Thus, considering PS from within the R–H perspective leads us to think about PS in a way that diverges from the typical understanding. Moreover, it makes some predictions and opens up wide possibilities for experimentation beyond the simple discrimination paradigms that are used in the majority of studies. For example, ‘pattern-separated’ representations in the DG should be important, not just for spatial/contextual memory, but for spatial/contextual analogues of the many object tasks that have been shown to be dependent upon PRh, some of which are mentioned above (e.g., Kesner et al., 2015).

Consideration of the R–H view of brain organization might also change the way researchers interpret the results of their studies. The most salient example, perhaps, is the need to consider the level of representation thought to be housed in the brain region one is considering. This means that the choice of stimuli used in experiments becomes critical. For example, if PRh is found not to be

involved in PS for locations/places, that does not mean it is not important for PS at all. It is – for object-level representations and stimuli. Similarly, if hippocampal dysfunction does not affect tasks for which object-level conjunctive representations are necessary (it doesn't; e.g., Kesner et al., 2015; Saksida et al., 2006, 2007), that does not mean it is not important for PS. It is – for location-level representations. This principle is as true for PS as it is for any other aspect of cognition, yet it continues to surprise us how often the assumptions of the cognitive processing module view lead researchers to think the choice of stimulus material in their experiments is irrelevant.

As another example, studies have tended to pit against one another tasks or cognitive abilities that according to R–H theory are underpinned by the same mechanism: the resolution of ambiguity (or interference) by conjunctive representations. For example in the area of neurogenesis, some researchers have asked: Does neurogenesis affect PS (discrimination at the behavioral level) or reduction of interference in memory? With our PRh work we have shown how the same conjunctive representations are useful for both discrimination and reduction of interference in memory. The same can be said of many aspects of cognition – including the persistence of memory – as explained above. Consideration of R–H, therefore, might lead researchers studying PS to frame their questions in a different way.

As a final example of the way consideration of R–H theory might lead researchers to design and interpret their studies differently, consider the case for separate types of PS; one for memory (reliant on the hippocampus), and another for perceptual discrimination. Hunsaker and Kesner (2013), for example, emphasize the importance of the ventral hippocampus in PS for memory of odors, but not perception, citing a study by Kesner, Hunsaker, and Ziegler (2011) showing that ventral hippocampus lesions spared pair-wise discrimination of similar odors, but impaired discrimination of even relatively dissimilar odors when a delay was imposed. However, as described above, Cowell et al. (2006) showed how conjunctive representations resolving interference can explain delay-dependent deficits (and the predictions of that model have been borne out in a number of experiments; e.g. Bartko et al., 2007; McTighe et al., 2010). The representations that do this are neither exclusively 'perceptual', nor 'mnemonic'; they are useful for all kinds of tasks that we refer to as tests of 'perception', 'memory', 'categorization', etc. Indeed on this view, we would predict that a lesion that compromised such conjunctive representations could generate exactly the pattern observed by Kesner et al. (2011): less similarity is required to produce a deficit when the task is combined with a delay that is also increasing the load on PS. Therefore from the perspective of R–H, it is not just that Kesner and colleague's conclusion that their results indicate 'mnemonic' but not 'perceptual' PS is unwarranted, it is that it is the wrong question to begin with, assuming as it does separate perceptual and mnemonic modules in the brain. However given that assumption, these authors approached it experimentally in the right way – by using tasks thought to tap these different assumed systems. Often the conclusion that the, say, hippocampus is involved in pattern separation for memory only, comes from nothing more than the assumption that the hippocampus does memory and nothing else (which we believe to be incorrect; Lee, Buckley, et al., 2005; Lee, Bussey, et al., 2005; Zeidman, Mullally, & Maguire, 2014). Furthermore the foregoing analysis underscores the need for evidence for PS to come from several levels of discriminability in a task where all other factors (such as delay) are held constant, and an interaction between group and discriminability obtained. Many studies on PS have not met this basic requirement, using on a single level of discriminability. Kesner et al. (2011) used four levels in the delay task. However all separations were impaired, thus providing little evidence for a role for the hippocampus in odor PS.

As a final comment, our work has focused almost exclusively on vision and the hierarchical organization of the VVS leading into the PRh and through to the hippocampus, but it is almost certainly the case that all of these considerations extend to modalities other than vision. Modalities begin to converge in the PRh; indeed there is some evidence for impaired tactile PS following lesions in this region (Ramos, 2014). However, representations in many unimodal areas are likely to be organized in this way, and the principles of conjunctive representations/ambiguity and PS would therefore apply equally to these other modalities. For example, the dorsal and ventral auditory processing streams appear to be hierarchically organized (Rauschecker & Scott, 2009; Warren, Wise, & Warren, 2005): the representations of specific speech sounds are encoded in posterior regions such as mid superior temporal gyrus (STG), whilst representations of the meaning of speech are represented in more anterior parts of the STG (Rauschecker & Scott, 2009). PS – as defined above – may be happening throughout many brain systems.

## Acknowledgments

LMS and TJB were funded by Medical Research Council/Wellcome Trust grant 089703/Z/09/Z. BAK was funded by Gates Cambridge and the Natural Sciences and Engineering Research Council of Canada (NSERC).

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