

The neural basis of overall similarity and single-dimension sorting

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ABSTRACT

The ability to group stimuli into meaningful categories is fundamental to natural behavior. Raw perceptions would be useless without an ability to classify items as, for example, threat or food. Previous work suggests that people have a tendency to group stimuli either on the basis of a single dimension or by overall similarity (e.g., Milton, F.N., Longmore, C.A., and Wills, A.J. (2008). Processes of overall similarity sorting in free classification. *J. Exp. Psychol. Hum. Percept. Perform.*, 34, 676–692.). It has recently been suggested that overall similarity sorting can engage similar rule-based processes to single-dimension sorting and, in addition, requires greater use of working memory (Milton, F.N., and Wills, A.J. (2004). The influences of stimulus properties on category construction. *J. Exp. Psychol. Learn. Mem. Cogn.*, 30, 407–415.). These predictions were tested in an event-related fMRI study of spontaneous categorization. Results showed a striking overlap of activation between overall similarity and single-dimension sorting indicating engagement of common neural processes. Furthermore, overall similarity sorting recruited additional activity in bilateral precuneus, right cuneus, left cerebellum, left postcentral gyrus, right thalamus and right ventrolateral frontal cortex (VLFC). Our findings suggest that overall similarity sorting can be the result of rule-based processes and highlight a potential role for right VLFC in integrating multi-dimensional sensory information to form conceptual categories.

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The ability to partition items into meaningful groups is one of the fundamental building blocks of everyday cognition. Categorization enables us to react to different objects in a similar manner and to make inferences about items we have never seen before. As a consequence, our raw perceptions would be of limited use without an ability to group items into meaningful categories. The categories we have must necessarily be highly constrained due to the virtually limitless number of ways even a small number of items can be partitioned. To illustrate this, just 10 items can be partitioned in over 100,000 ways. For this reason, a greater comprehension of the processes that underlie category formation is an important requisite for our understanding of human cognition.

One reasonable assumption is that people would have a preference to form categories that reflect the underlying structure of items we encounter outside the laboratory. Perhaps the two most influential theories of natural categories are the classical view and the family resemblance view. The “classical” view postulates that natural categories are made up of necessary and jointly sufficient features (e.g., Bruner et al., 1956). If an item has the necessary feature (or features) it can be considered a member of that category regardless of the rest of its properties. A family resemblance (overall similarity) structure (e.g., Wittgenstein, 1958) is organized around a number of

characteristic but not defining features. If an item has enough features characteristic of a category it can be considered a member of that category. The family resemblance view is generally regarded as a more compelling theory than the classical view due to the demonstration that many natural categories (e.g., dogs) appear to be organized around a family resemblance structure (e.g., Rosch and Mervis, 1975). In addition, family resemblance categories are considered a more information-rich category structure and have been considered especially useful for identification, inference, problem-solving, and other cognitive tasks (Murphy, 2002).

It is therefore surprising that initial studies showed that when participants are asked to classify a set of stimuli in the way that seems most natural, they have a strong tendency to form categories based on a single dimension (e.g., Ahn and Medin, 1992; Ashby et al., 1999; Medin et al., 1987), which appears more consistent with the classical view. For instance, Ahn and Medin (1992) showed that, for a variety of different stimulus sets, there was a strong bias toward single-dimension sorting and participants only sorted by overall similarity when the structure could not easily be sorted on the basis of a single dimension. More recently, however, research has shown that overall similarity sorting can be encouraged by a number of manipulations such as stimulus presentation procedure (Regehr and Brooks, 1995), stimulus structure (Pothos and Close, 2008), and stimulus properties (Milton and Wills, 2004).

The distinction between overall similarity and single-dimension sorting is consistent with the idea that there are two separate subsystems of concept formation. These subsystems have variously

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been termed analytic and non-analytic (J.D. Smith et al., 1984); similarity and rule-based (E.E. Smith et al., 1998); and implicit and verbal (Ashby et al., 1998). In the current paper we refer to these subsystems as analytic and non-analytic.

Traditionally, single-dimension sorting is believed to be the result of the analytic processing system. The analytic system requires selective attention and has been regarded as a relatively effortful and deliberate process whereby stimuli are broken down into their constituent dimensions and categorization is determined on the basis of a subset of these dimensions. The analytic system is also believed to activate verbal processes and require considerable working memory capacity because the rule itself must be maintained in working memory during the categorization process (E.E. Smith et al., 1998). In contrast, according to this distinction, overall similarity sorting is the result of a primitive, non-analytic system. The non-analytic system is considered to be a quick, automatic, holistic system where stimuli are processed as integral wholes (e.g., J.D. Smith et al., 1984), which requires relatively limited working memory capacity (e.g., E.E. Smith et al., 1998). There is a large body of behavioral and neuropsychological evidence in support of this distinction (e.g., Ashby et al., 1998; Filoteo et al., 2005; Kemler Nelson, 1984; Maddox and Ing, 2005; J.D. Smith et al., 1984; Ward, 1983; Zeithamova and Maddox, 2006; though see also Nosofsky and Johansen, 2000).

One of the best developed dual-process neuropsychological models of categorization is COVIS (competition between verbal and implicit systems; Ashby et al., 1998). In this model, the verbal (analytic) system is based on explicit reasoning that is under conscious control and the implicit (non-analytic) system uses procedural learning. COVIS assumes that the analytic, verbal, rule-based component occurs principally in the anterior cingulate and prefrontal cortices (e.g., Rao et al., 1997), whilst the non-analytic, multidimensional, information integration tasks are performed predominantly in the inferotemporal cortex and more specifically in the body of the caudate nucleus (Nomura et al., 2007) and the putamen in the basal ganglia (e.g., Shohamy et al., 2004). Recent work has also highlighted the role of inferior parietal cortex (e.g., Grossman et al., 2002) and lateral occipital cortex (Seeger and Cincotta, 2002) in non-analytic, similarity based categorization.

To date, however, relatively few neuroimaging studies have investigated the distinction between overall similarity and single-dimension sorting directly. One exception to this is an fMRI study by Tracy et al. (2003; though see also Nomura et al., 2007), who trained participants to categorize a set of pseudowords either by family resemblance (overall similarity) or by a single-dimension. In a subsequent scanning session, participants classified the stimuli according to these category structures. Single-dimension sorting implicated medial parietal lobe (assumed to reflect target monitoring), inferior frontal lobe (rule maintenance in working memory and feature selection), and anterior temporal lobe (sensitivity to isolated features). Family resemblance sorting activated left extrastriate cortex and medial cerebellar regions, which Tracy et al. (2003) took to be consistent with its multi-featural nature. Tracy et al. (2003) argued that their results were consistent with the idea that separate categorization systems are used to form these two category structures.

Recently, however, it has been proposed that the analytic/non-analytic distinction might be less clear than has traditionally been thought. Milton and Wills (2004) suggested that, under certain conditions, overall similarity sorting as well as single-dimension sorting can be the result of the analytic system. They argued that an additional way to categorize by overall similarity may be for people to break the stimulus down into its constituent dimensions and then integrate these dimensions into a “majority-features” decision rule. One fundamental prediction of this account is that overall similarity sorting should take more time and require greater use of working memory than single-dimension sorting due to the greater complexity of the categorization rule.

These predictions were supported by Milton et al. (2008). They showed that moderate time pressure can significantly decrease the prevalence of overall similarity sorting, and significantly increase the prevalence of single-dimension sorting. These findings support the contention that, at least under certain conditions, overall similarity sorting requires greater processing time than single-dimension sorting. Milton et al. (2008) also showed that the introduction of a moderate concurrent load reduced overall similarity sorting and increased single-dimension sorting. They suggested that the concurrent load interfered with the application of an overall similarity rule (which was assumed to require considerable working memory capacity), whilst still leaving sufficient resources to perform a simpler single-dimension strategy. These findings seem inconsistent with a non-analytic account of overall similarity sorting.

An ERP study conducted by Folstein and Van Petten (2004) is of some relevance to this proposal. Folstein and Van Petten used a variation of the procedure developed by Allen and Brooks (1991), which required participants to categorize stimuli using either a multi-dimensional rule provided by the experimenters or through exemplar-based learning. They showed that multidimensional classification strategies elicited a larger frontally distributed positivity than did strategies based predominantly on a unidimensional strategy. However, due to the relatively poor spatial resolution of ERP, it is unclear which particular regions of the frontal cortex were implicated in multidimensional strategies. Nevertheless, the findings of Folstein and Van Petten (2004) are consistent with the hypothesis that overall similarity categorization recruits frontal regions to a greater extent than single-dimension sorting.

The results of a PET study conducted by Patalano et al. (2001; see also E.E. Smith et al., 1998) are related to the current issue as well. Patalano et al. (2001) also used a variation of the Allen and Brooks (1991) procedure and showed that the rule-based condition recruited bilateral occipital cortex, right thalamus, right dorsolateral prefrontal cortex, and superior parietal cortex which indicate increased working memory, perceptual analysis and selective attentional demands for a rule-based strategy. The exemplar-based task activated extrastriate cortex and a region of the cerebellum. Whilst this study has been extremely influential, the results of their experiments do not directly contribute to our understanding of spontaneous strategy use (because the participants were provided with the multidimensional rule). As Patalano et al. (2001) note, an important next step is to examine strategy use in a broader range of categorization situations.

The current experiment is, as far as we are aware, the first neuroimaging study to investigate spontaneous categorization. In this study, we explore the neural basis of overall similarity sorting, which appears a particularly important question given that many natural categories are believed to be organized around such a structure. Our predictions were motivated by the findings of Milton et al. (2008), which indicated that overall similarity sorting can be an analytic process that requires greater working memory capacity than single-dimension sorting. We predicted that there would be an extensive overlap of regions recruited for both overall similarity and single-dimension sorting, supporting our hypothesis that both strategies were the result of similar analytic processes. This would be in contrast to a previous work, which showed very limited common activation between strategies (e.g., Tracy et al., 2003). Furthermore, we anticipated greater activation for overall similarity sorting compared to single-dimension sorting in regions associated with rule-based and working memory processes, such as frontal cortex, because the overall similarity rule is hypothesised to be more complex than the single-dimension rule.

The current study employs a between-subjects design, with participants being placed into the conditions of this design on the basis of whether they sorted by overall similarity or by a single dimension. Within-subjects designs are often preferable in principle but, in this particular case, employing a within-subjects design would

have resulted in some practical difficulties. Of particular importance, a within-subjects design would measure the neural correlates of shifting between different strategies as well as the processes that directly underlie these categorization strategies. Furthermore, in free classification studies, there is no corrective feedback to encourage participants to adopt a particular strategy, and hence one is reliant on factors such as stimulus properties and sorting procedure to manipulate participants into a particular sort strategy. These manipulations have only moderate effects on sorting behavior (see e.g., Milton and Wills, 2004), and this is problematic for a within-subjects design because those participants for whom the sorting style induction is unsuccessful have to be excluded. Using a between-subject design means a higher proportion of data collected can be utilized. An additional problem with a within-subjects design in this case is that participants are known to have a strong tendency to persist with their initial sort strategy on subsequent sorts (Milton and Wills, 2009).

Method

Participants

Thirty-one healthy, right-handed participants (12 male, 19 female) from the University of Exeter, ranging in age from 18 to 35 years, took part in the study. All participants gave informed consent and were paid £10 for their participation.

Stimuli

The stimuli had the same abstract structure (shown in Table 1) as that used by Medin et al. (1987). The stimulus set consisted of four binary-valued dimensions (D1–D4), and the stimuli were organized around two prototypical stimuli each representative of a category. These prototypes were constructed by taking all the positive values on the dimensions for one of the stimuli (1,1,1,1) and all the zero values on the dimensions (0,0,0,0) for the other category. The rest of the stimuli (one-aways) were mild distortions of the two prototypes in that they had three features characteristic of their category and one atypical feature characteristic of the other category. In total, there were 10 stimuli in the set. The stimuli (shown in Fig. 1) were artificial “lampshades” originally used in Milton and Wills (2004). The dimensions were the number of dots on the lampshade (few dots/many dots), the width of the stem (thick/thin), the hue of the top part of the base (dark blue/light blue), and the length of the lower part of the base (long/short).

fMRI data acquisition

Images were collected using a 1.5-T Phillips Gyroscan magnet, with a quadrature head coil. A T2*-weighted echo planar sequence was used (TR = 3000 ms, Te = 50 ms, flip angle = 90°, 31 transverse slices, 4 × 3 × 3 mm, ascending acquisition). A total of 240 volumes were acquired in each of the two runs per subject. An additional 5 “dummy” scans were performed at the beginning of each run prior to the start of the stimulus sequence. Standard volumetric anatomical MRI was

Table 1

The abstract stimulus set used

Category A				Category B			
D1	D2	D3	D4	D1	D2	D3	D4
1	1	1	1	0	0	0	0
1	1	1	0	0	0	0	1
1	1	0	1	0	0	1	0
1	0	1	1	0	1	0	0
0	1	1	1	1	0	0	0

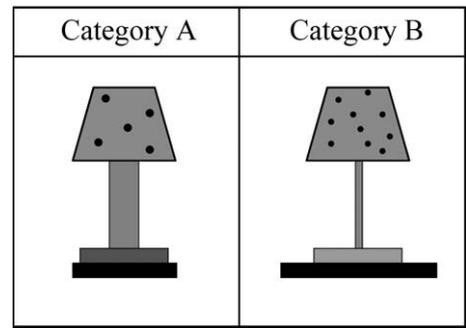


Fig. 1. The prototypes of the stimulus set used in the experiment.

performed after functional scanning by using a 3-D T1-weighted pulse sequence (TR = 25 ms, Te = 4.1 ms, flip angle = 30°, 160 axial slices, 1.6 × 0.9 × 0.9 mm).

Procedure

Participants were first introduced to the stimuli with a pre-sort matching-pairs procedure used previously by Milton and Wills (2004). In this procedure, 20 cards were randomly spread out in an array in front of the participant. These cards consisted of the 10 stimuli in the set and an identical copy of each of them. Participants had to match these stimuli into identical pairs without feedback. When the participant felt that the pairs had been matched correctly, the matches were then examined by the experimenter; if there were any mistakes participants were asked to match the pairs again. The purpose of this task was to ensure that participants could fully distinguish the four feature pairs, because if the dimensions had not all been identified an overall similarity sort might be difficult to carry out.

The categorization phase of the study took place inside the scanner. Visual stimuli were presented on a back-projection screen positioned at the foot end of the MRI scanner and viewed via a mirror mounted on a head coil. Button-press responses and reaction times were measured using two fiber-optic button boxes held in the participants' right and left hands. E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA, <http://www.pstnet.com>) was used for the presentation and timing of stimuli and collection of reaction times and response data.

A free matching categorization task, similar to that used by Milton et al. (2008), was employed. Participants were asked to sort the stimuli into two categories in the way they thought most appropriate. They were told that there were many ways in which the stimuli could be split and there was no one correct answer. No feedback was given on their responses.¹

The current study employed an event-related design alternating categorization trials with a baseline state (rest). Each trial began with a blank screen lasting between 0 and 12 s, followed by a fixation cross for 1000 ms. The two prototypes were then presented on the screen. The category A prototype was presented in the top left portion of the screen, and the category B prototype was presented in the top right portion of the screen. The category that each prototype represented was fixed across participants. Directly below the prototypes, one of the stimuli in the set was presented in the lower middle portion of the screen for 4000 ms. Participants were instructed not to make a response during this time. This screen was immediately followed by a question mark which remained on the screen for 5000 ms. During this

¹ Note that the current procedure is not free classification in its strictest sense (e.g., Bersted, Brown, and Evans, 1969) — participants are given the category prototypes and told how many categories should be used (i.e. two). Nevertheless, participants were provided with no feedback on their responses and encouraged to sort the stimuli in the way that seemed most natural. In line with Regehr and Brooks (1995), and with our own previous usage (Milton and Wills, 2004), we describe the current procedure as a form of free classification.

time period, participants were asked to classify the stimulus into either category A (by pressing the left response box) or into category B (by pressing the right response box). If participants failed to respond during this interval, a message appeared on the screen saying “Time Out!!”

Participants were presented with a total of 80 stimuli in 8 blocks of 10 trials. In each block, every stimulus in the set was presented once in a random order. At the end of each block a message appeared on the screen for 20 s saying “That is the end of the block. Please take a short break.” This was followed by a message lasting for 5000 ms instructing participants to “Get ready to start the next block.” The session was divided into two scanning runs, each lasting 12 min, and four blocks of trials were presented in each run. After each run, participants were asked to describe as precisely as possible the way in which they sorted the stimuli.

Behavioral analysis

Each participant was classified as having produced one of the sort types described below. These sort types are very similar to those employed by Regehr and Brooks (1995) and are identical to those employed by Milton and Wills (2004).

A *single-dimension* sort is based on a single dimension of the stimulus. It does not matter which dimension is used as the basis of sorting, so long as all the positive values for the chosen dimension were in one category and all the zero values for that dimension were in the other category. Additionally, in order to receive this classification, the participant had to describe their sort as being based on a single dimension.

Participants were considered to have produced a *one-away single-dimension* sort if they described their sorting as being driven by a single dimension but only nine of the classifications were consistent with this strategy. The other stimulus was either misclassified or “timed out” due to participants taking too long to respond.

An *overall similarity sort* has a structure identical to that shown in Table 1. To receive this classification, the participant had to place each of the prototypes, along with their derived one-aways, into separate categories without error. Additionally, participants had to describe their sort as being based either on general similarity or on the premise that they placed each item into the category with which it had more features in common.

A *one-away overall similarity* sort is similar to the one-away single-dimension sort with the exception that one of the stimuli was either misclassified or “timed out” in a sort that was otherwise by overall similarity.

Any classifications produced by a participant other than those described above were classified as *other* sorts, even if the description given by the participant fitted one of the sorts described above.

Analysis of fMRI data

Data analysis was carried out using SPM5 software (www.fil.ion.ucl.ac.uk/spm). Functional images were corrected for acquisition order, realigned to the first volume and resliced using fourth-degree spline B interpolation to correct for motion artifacts. A mean image created from the realigned volumes was coregistered with the structural T1 volume and the structural volumes were spatially normalized. The spatial transformation was applied to the realigned T2* volumes which were spatially smoothed using a Gaussian kernel of 8 mm full-width half maximum. Data were high-pass filtered (128 s) to account for low frequency drifts. The BOLD response was modeled by a canonical hemodynamic response function together with the temporal and dispersion derivatives. The six head movement parameters were included as confounds. First-level linear contrasts of parameter estimates for each voxel were taken to the second-level and a random effects analysis performed.

A conjunction analysis was performed to examine the areas of common activation for overall similarity and single-dimension sorting. To do this, we conducted two one-sample *t*-tests contrasting overall similarity sorting to baseline (OS>Baseline) and single-dimension sorting to baseline (1-D>Baseline). The rest period was used as the baseline, as in, for example, Tracy et al. (2003). The threshold for each of these contrasts was set at $p < .001$ (uncorrected). These contrasts were then combined via a logic “AND” function using the minimum statistic compared to the conjunction null hypothesis (MS/CN; Nichols et al., 2005). In other words this analysis revealed only those regions that were significantly activated in overall similarity sorts compared to baseline AND those regions which were also significantly activated in single-dimension sorts compared to baseline. This technique has often been used to assess common activation between tasks (e.g., Bartels et al., 2008; Iseki et al., 2008; Van den et al., 2008).

We also compared overall similarity sorting to single-dimension sorting (OS>1-D), and single-dimension sorting to overall similarity sorting (1-D>OS) using two-sample unrelated *t*-tests. For these between-subject analyses, we applied a threshold of $p < .001$ (uncorrected) with a voxel cluster size threshold of 5 (as in, for example, Ebisch et al., 2008; Spence et al., 2008; Wendelken et al., 2008; Yonelinas et al., 2005; see also Forman et al., 1995). The *x,y,z* coordinates of all activation clusters were transformed from normalized MNI space (i.e., SPM coordinates) to Talairach space (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>) to establish the site of activation in relation to the atlas of Talairach and Tournoux (1988).

Results

Behavioral analysis

Trials for which participants failed to respond during the 5 second response period were excluded from the behavioral analyses. The percentage of trials excluded was low for all participants ($M = 1.79\%$, $SD = 2.66\%$).

For each participant, the sort for each of the 8 blocks was analyzed separately according to the criteria outlined above. Sorts were placed into one of three categories: overall similarity, single-dimension, and other (the overall similarity and single-dimension categories were combined with their respective one-aways, as in Milton et al., 2008). Participants who sorted the majority of the blocks by one of these strategies were classified according to the strategy they used. Participants who did not show any consistent strategy were placed into the other category and excluded from subsequent analyses (due to the low sample size and diversity of responding behavior). In total,

Table 2

Common regions of activity for overall similarity and single-dimensional sorting

Region	Cluster size	BA	Talairach coordinates			z-score
			x	y	z	
Right posterior cerebellum	9629	–	33	–56	–12	>8.00
Right middle occipital gyrus		19	42	–78	7	7.83
Left middle occipital gyrus		19	–33	–84	18	7.76
Anterior cingulate	115	23	0	–28	24	6.23
Right sub-lobar thalamus	1145	–	21	–29	4	6.07
Left sub-lobar thalamus		–	–12	–20	9	5.88
Left brainstem		–	–6	–20	–1	5.47
Left dorsolateral frontal cortex	66	46	–42	30	23	5.17
Left dorsolateral frontal cortex		46	–48	25	26	3.24
Left sub-lobar insula	25	13	–36	–2	11	4.82
Right anterior cerebellum	29	–	6	–39	–26	4.21
Right anterior cerebellum	12	–	0	–59	–27	3.94
Left brainstem	14	–	6	–39	–26	3.76
Right middle prefrontal cortex	7	10	42	41	12	3.37

Note. BA = Brodmann's area. Indented rows indicate voxels in the same cluster as the non-indented row above them.

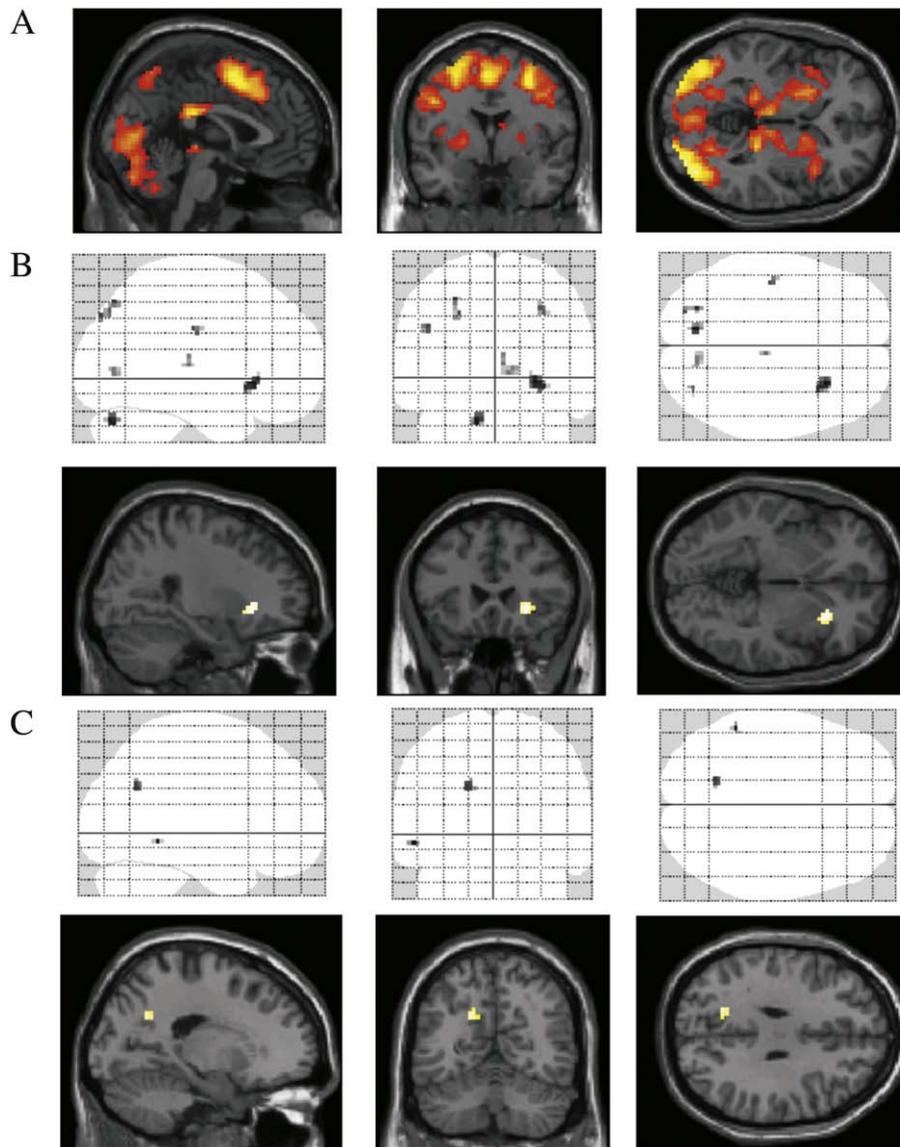


Fig. 2. a) Activation common to both types of categorization; b) significant activation for overall similarity sorting compared to single-dimension sorting; c) significant activation for single-dimension sorting compared to overall similarity sorting.

17 participants sorted consistently by overall similarity, 10 by a single dimension, and 4 were placed in the other category. An independent sample *t*-test revealed that there was no significant difference in response times between overall similarity and single-dimension sorters, $t(25) = .21, p > .5$, which may reflect that the stimulus presentation time (4000 ms) was generally sufficient for participants to complete the decision process.

Imaging analyses

The conjunction analysis examining the shared activity for overall similarity and single-dimension sorting revealed that a number of areas were commonly recruited (Table 2; Fig. 2a). There was significant common activity in bilateral posterior and anterior cerebellum, extending into bilateral occipital cortex, bilateral superior parietal cortex, left brainstem, and bilateral thalamus (including the pulvinar). In addition, there was common activity in the anterior cingulate, left insula, left dorsolateral frontal cortex (DLFC), and right middle prefrontal cortex.

The regions exhibiting greater activation for overall similarity sorting compared to single-dimension sorting (shown in Table 3; Fig.

2b) included right ventrolateral frontal cortex (VLFC), left postcentral gyrus, medial dorsal thalamus, bilateral precuneus, right cuneus, and left cerebellum. A contrast comparing single-dimension to overall

Table 3
Significant activation for overall similarity sorting compared to single-dimension sorting

Region	Cluster size	BA	Talairach Coordinates			z-score
			x	y	z	
Right ventrolateral frontal cortex	30	47	27	23	-4	3.87
Right anterior insula		47	33	17	-6	3.73
Left cerebellum	19	-	-12	-71	-21	3.82
Left precuneus	11	7	-27	-67	50	3.69
Left precuneus		7	-24	-77	43	3.58
Left postcentral gyrus	5	6	-45	-16	31	3.55
Right precuneus	7	7	30	-71	45	3.47
Right sub-lobar thalamus	5	-	6	-20	9	3.38
Right cuneus	12	18	9	-69	6	3.35

Note. BA = Brodmann's area. Indented rows indicate voxels in the same cluster as the non-indented row above them.

Table 4
Significant activation for single-dimension sorting compared to overall similarity sorting

Region	Cluster size	BA	Talairach Coordinates			z-score
			x	y	z	
Left sub-gyral temporal lobe	5	37	−53	−45	−6	4.28
Left superior parietal lobe	10	31	−18	−57	30	3.91

Note. BA = Brodmann's area.

similarity sorting (see Table 4; Fig. 2c) revealed significantly greater activation in a region of left superior parietal lobe and in left sub-gyral temporal lobe.

General discussion

The present study revealed an extensive overlap of activity between overall similarity and single-dimension sorting, which suggests that both sort types engaged a number of common neural processes. Common regions activated included the cerebellum, bilateral occipital cortex, bilateral thalamus (including the pulvinar), and the midbrain. In addition, there was a significant activation in left insula, anterior cingulate, and left DLFC.

Many of the regions commonly recruited have been linked to higher-order processing. Bilateral occipital cortex activation likely reflects perceptual processing of the stimuli; Patalano et al. (2001) found similar activation in a multi-dimensional rule task, which they linked with perceptual testing in rule application. The thalamus (and in particular the pulvinar) is believed to be a key link in relaying information between cortical areas (Sherman, 2007) and has been implicated in selective attention (Laberge, 1995; Woldorff et al., 2004), and rule use (Grossman et al., 2002; Patalano et al., 2001). The insula is linked to goal maintenance and working memory demands (Dosenbach et al., 2006). The anterior cingulate has been associated with rule selection (Posner and Petersen, 1990), whilst the DLFC has been linked with increased working memory demands (Owen, 2000) and rule use (e.g., Patalano et al., 2001). Taken together, this pattern of common activation suggests that both overall similarity and single-dimension sorting engage similar analytic processes.

In addition to this extensive overlap of activation, overall similarity sorting exhibited increased activation in a number of regions compared to single-dimension sorting. Of particular interest was the additional activation in right VLFC. Right VLFC has previously been linked to a myriad of important cognitive tasks such as inhibitory processes (e.g., Hodgson et al., 2007), conditional learning mechanisms (e.g., Passingham et al., 2000), rule use (Bunge, 2004; Grossman et al., 2002), working memory (Aalto et al., 2005), and memory retrieval (Fletcher et al., 1998).

A similar region has previously been implicated in categorization by non-human primates. Specifically, Freedman et al. (2001) showed that the lateral frontal cortex has an important role in the categorization of multidimensional stimuli in monkeys. In addition to this, left VLFC has been shown to activate more for complex rules than for simpler rules (Bunge, 2004). The current study extends these findings by demonstrating that right VLFC is implicated in the spontaneous application of a multi-dimensional classification rule in humans. The role of right VLFC may be to bind a number of dimensions into a "majority-features" decision rule.

In addition to the increased activation in right VLFC, we observed greater activation for overall similarity sorting relative to single-dimension sorting in left cerebellum, left postcentral gyrus, right thalamus, bilateral precuneus, and right cuneus. The cerebellum has previously been linked to rule use (e.g., Patalano et al., 2001) as well as a number of different cognitive processes such as working memory, explicit learning, and language (c.f., Desmond and Fiez, 1998). Left

postcentral gyrus activates more in a verbal working memory task than in a spatial working memory task (Rama et al., 2001).

The thalamus and precuneus have both been shown to exhibit increased activity in a categorization task (Sachs et al., 2008). The extra thalamus activity in the present study may reflect the increased attentional demands that overall similarity sorting is believed to require. The precuneus has been linked to increased memory demands (e.g., Cavanna and Trimble, 2006) and the orienting of visual spatial attention (Woldorff et al., 2004) which is consistent with the requirements of analytic overall similarity sorting. In line with this argument, Patalano et al. (2001) observed similar bilateral activations for multidimensional rule-based categorization. The extra activity in the cuneus may reflect greater perceptual processing requirements for overall similarity sorting compared to single-dimension sorting.

Two areas exhibited greater activity for single-dimension sorting compared to overall similarity sorting. These regions were in left sub-gyral temporal lobe and in left superior parietal lobe. The left sub gyral temporal lobe has previously been linked to the categorization of non-living objects (Perani et al., 1999), whilst a similar region in the left superior parietal lobe has been implicated in selective spatial attention (Corbetta et al., 2000). This appears particularly useful for single-dimension sorting where participants focus on the particular spatial location of the relevant dimension and exclude the remaining dimensions from the decision process.

The regions recruited to a greater extent by overall similarity than by single-dimension sorting in the present study have previously been implicated in a number of processes (such as working memory, rule-use, and selective attention) that have been linked to the analytic processing system (e.g., E.E. Smith et al., 1998). The extensive overlap of activation between overall similarity sorting and single-dimension sorting in the current study also supports the argument that both sort types can be the result of similar processes (Milton and Wills, 2004). Our findings therefore suggest that the processing distinction between overall similarity and single-dimension sorting may not be as clear as has traditionally been thought. One key implication of the present study, consequently, is that it appears necessary to exercise caution when assigning processing strategies on the basis of sort type alone as has sometimes been the case in previous categorization studies (e.g., Kemler Nelson, 1984; J.D. Smith and Shapiro, 1989).

The current results provide limited information concerning the relative effort that overall similarity and single-dimension sorting require. In the current procedure, participants were required to wait until the stimulus disappeared from the screen before responding. This technique was employed in order to better equate the processing time between conditions, which could otherwise have influenced the pattern of activity. This is a likely explanation for the non-significant difference in response times between conditions. It also means that the current study does not provide a direct measure of the relative processing time that overall similarity and single-dimension sorting require, which would provide a valuable insight into the level of effort the two strategies entail. However, recent behavioral work on free classification shows that overall similarity sorting can be a more time-consuming process than single-dimension sorting which indicates that, at least under certain conditions, overall similarity sorting may be the more effortful strategy (Milton et al., 2008).

Whilst our results suggest there may not be as clear a distinction between the processes of overall similarity and single-dimension sorting as is commonly assumed, it is not our intention to challenge the compelling evidence that there may also be a non-analytic system of overall similarity sorting. Previous work has provided behavioral evidence for the existence of both analytic and non-analytic systems of overall similarity sorting (Milton et al., 2008) and we suggest that the processing system that is applied to form overall similarity categories may be strongly mediated by task demands such as stimulus structure and processing time. For instance, there is evidence

that, under extreme time pressure, overall similarity sorting is the result of a quick, automatic, non-analytic system (Milton et al., 2008; J. D. Smith et al., 1984; Ward, 1983). One implication of these findings is that, under such conditions, there should be a greater neural distinction between overall similarity sorting and single-dimension sorting, with the particular regions activated for overall similarity sorting more typical of what has previously been observed for such a category structure (e.g., Tracy et al., 2003).

The suggestion that overall similarity sorting can be the result of a complex rule can potentially be accommodated by COVIS. In many previous applications of COVIS, the rule-based system utilizes only a single dimension (e.g., Maddox et al., 2003; Waldron and Ashby, 2001). This constraint is, however, mainly for convenience and multidimensional rules have sometimes been applied (e.g., Zeithamova and Maddox, 2006). Indeed, Ashby et al. (1998) note that any rule that is verbalizable can be accommodated by the verbal system, although the more complex the rule, the less likely it is to be used. When participants were asked to describe their strategy at the end of the scanning session, all the overall similarity sorters were able to clearly verbalize the majority-features rule without aid from the experimenter. This supports the argument that our results can potentially be accommodated by COVIS.

In summary, the current study, using a free matching task, revealed a striking neural overlap between overall similarity and single-dimension sorting which provides evidence that these two strategies can engage common neural processes. In addition, overall similarity sorting recruited a number of additional regions, including right VLFC, compared to single-dimension sorting. The pattern of activation provides evidence for the contention of Milton and Wills (2004) that overall similarity sorting can be the result of a rule-based analytic system that engages working memory. Right VLFC has previously been implicated in diverse cognitive tasks and the present findings suggest that a further role of this region may be to integrate multiple-sensory information to form conceptual categories.

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