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Towards an understanding of the mechanisms of weak central coherence effects: experiments in visual configural learning and auditory perception

Kate Plaisted[1*], Lisa Saksida[1], José Alcántara[1] and Emma Weisblatt[2]

[1]*Department of Experimental Psychology, University of Cambridge, Downing Site, Cambridge CB2 3EB, UK*
[2]*Department of Psychiatry, Developmental Psychiatry Section, University of Cambridge, Douglas House, Cambridge CB2 2AH, UK*

The weak central coherence hypothesis of Frith is one of the most prominent theories concerning the abnormal performance of individuals with autism on tasks that involve local and global processing. Individuals with autism often outperform matched nonautistic individuals on tasks in which success depends upon processing of local features, and underperform on tasks that require global processing. We review those studies that have been unable to identify the locus of the mechanisms that may be responsible for weak central coherence effects and those that show that local processing is enhanced in autism but not at the expense of global processing. In the light of these studies, we propose that the mechanisms which can give rise to 'weak central coherence' effects may be perceptual. More specifically, we propose that perception operates to enhance the representation of individual perceptual features but that this does not impact adversely on representations that involve integration of features. This proposal was supported in the two experiments we report on configural and feature discrimination learning in high-functioning children with autism. We also examined processes of perception directly, in an auditory filtering task which measured the width of auditory filters in individuals with autism and found that the width of auditory filters in autism were abnormally broad. We consider the implications of these findings for perceptual theories of the mechanisms underpinning weak central coherence effects.

Keywords: perception; configuration; local; global; integration

1. INTRODUCTION

Throughout the history of experimental research in autism, there has been an interest in the perceptual and attentional abnormalities that have been widely reported by clinicians, parents of children with autism and individuals with the disorder themselves (Kanner 1943; Grandin & Scariano 1986; Sainsbury 2000; Myles *et al.* 2000). Early research focused on possible sensory differences in the autistic population (Goldfarb 1961; Ornitz 1969), while later research examined possible differences in selective attention (Lovaas *et al.* 1979). More recently, research on perceptual and attentional aspects of autism has been inspired by the conceptualization by Frith (1989) of these abnormalities as 'weak central coherence'. Her hypothesis postulates a weakness in the operation of central systems that are normally responsible for drawing together or integrating individual pieces of information to establish meaning, resulting in a cognitive bias towards processing local parts of information rather than the overall context.

It has been argued that weak central coherence can be seen at both 'low' and 'high' levels (Happé 1996, 1997). An example of 'low' level weak central coherence that has been cited is the exceptionally good performance of individuals with autism on the embedded figures task and the block design subtest of the Wechsler intelligence scales (Shah & Frith 1983, 1993; Happé *et al.* 2001), as success on these tasks requires the participant to process the local parts of the stimuli and to ignore the visual context in which the stimuli are presented. The term 'high' level weak central coherence has been used to describe studies of contextual processing, such as mispronunciation of homographs in sentence context and drawing incorrect bridging inferences between two sentences by individuals with autism (Happé 1997; Jolliffe & Baron-Cohen 1999). Thus, 'low' level weak central coherence has been used to refer to processes such as perception, learning and attention whilst 'high' level weak central coherence has been used to refer to linguistic and semantic processes.

The idea of weak central coherence clearly and neatly characterizes the style of stimulus processing that could give rise to this pattern of responding—a piecemeal approach that results in superior performance on some tasks and poor performance on others. However, what is less clear is the nature of the mechanisms of weak central coherence that give rise to these effects and, furthermore, what single cognitive mechanism could give rise to both 'low' and 'high' level weak central coherence. Attempts to address this question have so far been limited to searching for a mechanism of 'low' level weak central coherence. For example, some researchers have indicated that the mechanism might be a 'narrow' spotlight of attention, which

*Author for correspondence (kcp1000@hermes.cam.ac.uk).

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normally serves to enhance processing at a particular location in attentional space and operates to bind together or integrate separate features (Townsend & Courchesne 1994). However, in one type of test of the spotlight of attention, the conjunctive visual search task, a series of studies has generally found that children with autism *outperform* typical children (Plaisted *et al.* 1998*a*; O'Riordan & Plaisted 2001). Another proposal has been that right-hemisphere attentional processes which may serve to process the overall form of a visual stimulus (Lamb *et al.* 1990) may be compromised in autism and thus constitute the locus of the 'low' level weak central coherence mechanism. These studies have employed hierarchical stimuli (such as a large triangle comprised of small squares) and participants are required to respond to the overall form of the stimulus (referred to as the global level) or the constituent features (referred to as the local level). In typical individuals, a common effect is that the global level of the stimulus dominates responding, with slower and less accurate responding to the local level (Navon 1977). The literature comparing individuals with and without autism has produced mixed results. Nonetheless, two findings have been replicated across studies. The first is that individuals with autism can respond to the global level of a hierarchical stimulus in the same way as comparison individuals (Mottron & Belleville 1993; Ozonoff *et al.* 1994; Plaisted *et al.* 1999). The second is that, under some circumstances, individuals with autism show faster and more accurate responding to the local level than comparison individuals (Mottron & Belleville 1993; Plaisted *et al.* 1999). Furthermore, although most of these studies have been conducted in the visual domain, an analogous finding has been reported in the auditory domain (Mottron *et al.* 2000). The fact that individuals with autism can process the global level of a stimulus normally is clear evidence that those attentional mechanisms responsible for global processing are not deficient in autism and thus cannot be the locus of 'low' level weak central coherence. However, the fact that individuals with autism can show enhanced local processing as well as normal global processing challenges the central idea of the weak central coherence hypothesis, that a local-level processing bias results from a deficit in global-level processing.

These challenges to the weak central coherence hypothesis have led to alternative proposals for the mechanism that underpins enhanced local processing in autism on tasks such as the embedded figures and block design. One suggestion has been that their performance may result from abnormal perceptual processing in autism, which serves to enhance the salience of individual stimulus features and allows greater acuity in their representation but does not compromise processing of global configurations. We have offered this possibility as an explanation for enhanced discrimination effects in autism that we have observed in a difficult perceptual learning discrimination task and conjunctive search tasks in which there is high perceptual similarity between targets and accompanying distracters (Plaisted *et al.* 1998*b*; O'Riordan & Plaisted 2001; Plaisted 2001). Thus, differences in perception that enhance feature processing may constitute an alternative hypothesis to 'low' level weak central coherence. As this hypothesis is limited to perception, it makes no prediction (unlike weak central coherence) that processing the global level of a stimulus would be abnormal, since processing at that level would rely on post-perceptual mechanisms such as grouping and integration (see Palmer & Rock (1994), for a theory of the mechanisms involved in the processing of complex stimuli). We begin this paper by comparing the two hypotheses in configural and elemental learning tasks in the visual domain. In the second part of the paper, we directly examine the possibility that auditory perception in autism is abnormal using an auditory filtering task.

2. CONFIGURAL AND FEATURE PROCESSING

At the heart of the weak central coherence hypothesis is the idea that individuals with autism have deficits in the ability to integrate disparate features in order to derive the overall global configuration of the stimulus. This kind of deficit has clear implications for the way in which the meaning or significance of stimuli can be interpreted: the significance of a stimulus is rarely determined by a single distinctive feature but rather a particular configuration of features. Furthermore, some features of one stimulus can also configure with other features in a second stimulus, defining a different significance. An example that may be of relevance in autism is recognizing the emotional significance of a facial expression: different expressions share some features, but their particular configurations denote particular emotional expressions. For example, a down-turned mouth configured with a frown denotes sadness, a frown configured with narrowed eyes denotes a cross expression and a down-turned mouth with narrowed eyes indicates disgust.

This configural problem can be stated more formally as follows: features AB = expression X, features BC = Y and AC = Z. Models of configural learning indicate that when the significance of a stimulus is determined only by the combination of two or more features, those features are unified in a single representation as a configuration, and this configural representation is qualitatively different from the separate representations of each individual feature (Pearce 1994; Bussey & Saksida 2002). Thus, these models would identify abnormalities in configural representations as the locus of weak central coherence in autism. By contrast, the perceptual hypothesis predicts no deficit in configural processing; however, because this hypothesis states that features are more salient and acutely represented, it predicts that the significance of stimuli that are defined solely by the presence of particular features, rather than the configuration of features, would be easily acquired by an individual with autism, and perhaps more easily than individuals without autism. We tested these predictions in two tests of configural and feature processing, comparing high-functioning children with autism with normally developing children, matched for mental age.

3. EXPERIMENT 1: THE BICONDITIONAL CONFIGURAL DISCRIMINATION

Children were presented with two discrimination tasks—one which required configural processing for its solution and another in which the solution could be derived from the simple association between individual

Table 1. Participant characteristics

group	age (yrs : mths)	RSPM scores
experiment 1		
autistic ($N = 9$)		
mean	10 : 6	29
s.d.	1 : 1	7.77
typical ($N = 9$)		
mean	10 : 2	30.44
s.d.	1 : 1	7.6
experiment 2		
autistic ($N = 12$)		
mean	9 : 6	31.83
s.d.	1 : 2	8.59
typical ($N = 12$)		
mean	9 : 6	30.33
s.d.	1 : 2	7.5

features and a left or right key press action. The configural task was a biconditional discrimination involving stimuli composed of two features. In this task, no single feature defined the left or right key press action. The stimuli and associated actions can be represented as follows: Features A and B → press left, features B and C → press right, features C and D → press left, features A and D → press right. Hence, each individual feature A, B, C or D is equally associated with both left and right key presses, and the solution to the problem can be solved only by considering the configuration of the two features combined. The feature discrimination had the following structure: features S and T → left, U and V → right, WX → left, YZ → right. Thus, each feature diagnosed the appropriate key press action.

(a) *Methods*

(i) *Participants*

A group of nine high-functioning children with autism and a group of nine typically developing children participated. All children in the group with autism had received a diagnosis of autism by trained clinicians using instruments such as the Autism Diagnostic Interview (Le Couteur *et al.* 1989) and met established criteria for autism, such as those specified in DSM-IV (American Psychiatric Association 1994). None of the children in either group had received any other psychiatric diagnosis. Each child in the autistic group was pairwise matched with a child in the typically developing group for CA and nonverbal IQ using the RSPMs (Raven 1958). Details of the CAs and RSPM scores for each group are provided in the top half of table 1.

(ii) *Apparatus and stimuli*

The stimuli were generated by a Dell Latitude LM portable PC and displayed in the centre of a 14 inch monitor. Participants responded on each trial by pressing either the '.' key or the 'x' key on the keyboard. Coloured geometric shapes were used for both the biconditional configural discrimination and the feature discrimination. For the biconditional discrimination, four stimuli were used, each comprising a colour feature and a shape feature. Stimulus AB was a blue bar, stimulus BC was a red bar, stimulus CD was a red circle and stimulus AD was a blue circle. For the four stimuli used in the feature task, stimulus ST was a pink star, stimulus UV was an orange square, stimulus WX was a yellow triangle and stimulus YZ was a purple cross. In both tasks, the children sat 140 cm in front of the computer display.

(iii) *Design and procedure*

Each child was given two testing sessions, separated by an interval of not less than 2 days. During the first session, the RSPM was administered, followed by either the biconditional or the feature discrimination. In order to counterbalance for practice or fatigue effects, four of the children in each group received the biconditional discrimination first and the feature discrimination second and the remaining children received the two tasks in reverse order.

For both discriminations, the child's task was to learn which stimuli were associated with a left key press (by pressing the 'x' key) and which were associated with a right key press (by pressing the '.' key). In the biconditional task, stimuli AB and CD were associated with the left key and stimuli BC and DA were associated with the right key. This ensured that each feature (colour or shape) was equally associated with both left and right key presses, so that the task could be solved only by reference to the configuration of two features. In the feature discrimination, stimuli ST and UV were associated with the left key, and stimuli WX and YZ were associated with the right key.

At the start of each test, the children were shown each stimulus separately and told that their task was to find which of the two keys they should press after each type of stimulus. They were shown that if they pressed the 'correct' key, the computer would display a large tick in the centre of the screen and make a chirping sound whereas if they pressed the 'incorrect' key, the computer would display a cross and make an 'uh-oh' sound. Once children had indicated that they understood the task, the test trials began. In each task on each trial, a stimulus was presented in the centre of the screen until a response had been made. The feedback for that trial was then immediately presented for 500 ms, followed by a blank screen for 500 ms. After this intertrial interval, the next stimulus was presented. The computer was programmed to present a minimum of 32 trials and a maximum of 128 trials and calculated the percentage correct score within every 16-trial block. If children had reached a criterion of 12 out of 16 trials correct in any 16-trial block (following the first 16 trials) the programme terminated. Within every 16-trial block, each of the four stimulus types appeared on four trials. Stimulus trial types were randomly intermixed in each 16-trial block. Error data were recorded on each trial.

(b) *Results*

The average percentage of correct trials for each group are presented in figure 1. The graph indicates that there was no difference between the two groups on the biconditional discrimination task but that the group with autism performed better on the feature discrimination task compared with the typically developing group. These data were analysed by mixed ANOVA, with group (autistic and typical) and order (biconditional task first followed by feature task and vice versa) as between-participants factors

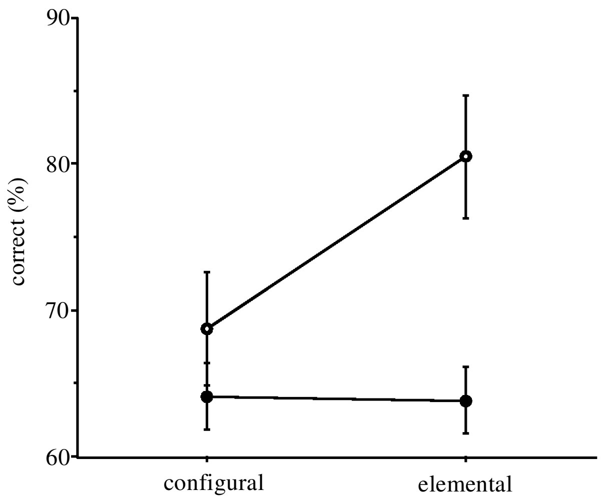

Figure 1. Average per cent correct for each group in the biconditional configural discrimination and the feature discrimination in experiment 1. The error bars represent s.e.m. White circles, autistic; black circles, control.

and discrimination type (biconditional and feature) as a within-participants factor. There was a significant main effect of group ($F_{1,14} = 6.24$, $p < 0.03$) and discrimination type ($F_{1,14} = 12.63$, $p < 0.004$) and a significant interaction between group and discrimination type ($F_{1,14} = 20.23$, $p < 0.0006$). There were no other significant main effects or interactions. The main effect of group was due to the fact that, overall, the group with autism performed better than the typically developing group and the effect of discrimination type showed that the feature task was easier than the configural task. However, the interaction between group and discrimination type indicated that this was the case for the group with autism only. This was confirmed by simple effects analysis of the interaction: there was a significant effect of group on the feature task ($F_{1,16} = 5.83$, $p < 0.03$) but not on the biconditional task, and a significant difference for the autistic group between their performance on the two tasks ($F_{1,16} = 39.19$, $p < 0.0001$) but no difference for the typically developing group.

(c) *Discussion*

The finding that the children with autism performed better than the typically developing children on the feature task and found this task easier than the biconditional discrimination is consistent with the idea that individual features are processed extremely efficiently in autism and the hypothesis that perception of features is highly acute. Furthermore, the lack of difference between the two groups of children on the biconditional discrimination task indicates that children with autism do not have a deficit in learning about the significance of configurations of features. Nonetheless, it is a possibility (which we explore further following the next experiment) that the superior processing of the individual features of shape and colour in the biconditional discrimination may have interfered with learning the configurations in that task and that the performance of the group with autism on the biconditional task might otherwise have been better than observed. The question is whether this constitutes evidence for the weak central coherence hypothesis: possibly, except that weak central coherence would predict that the interference from the features should be sufficiently great to impair performance substantially on the biconditional task relative to the typically developing group.

4. EXPERIMENT 2: THE FEATURE–CONFIGURATION PATTERNING TASK

It could be argued that the biconditional discrimination task in the previous experiment in § 3 was too simple to challenge any deficiency in configural processing in autism. In order to examine configural processing further, we presented another type of configural discrimination task that included both feature and configural trials. In the feature-configuration patterning task, on feature trials a stimulus, either A or B, is presented and each is followed by the same outcome (i.e. A → left press, B → left press). On configural trials, stimuli A and B are presented together followed by a difference outcome (i.e. AB → press right). A feature solution to this task is therefore not possible since learning that the individual features A and B are associated with the left key press would signify (even more strongly) a left key press when the features A and B are presented together. Instead, the configural association (AB → right key) must be learned separately from the individual feature-action associations.

(a) *Methods*

(i) *Participants*

A group of 12 high-functioning children with autism and a group of 12 typically developing children participated. As before, all children in the group with autism met established criteria for autism, such as those specified in DSM-IV (American Psychiatric Association 1994) and had received a diagnosis of autism by trained clinicians. None of the children in either group had received any other psychiatric diagnosis. The children were pairwise matched across groups for CA and RSPM scores. Details of the CAs and RSPM scores for each group are provided in the bottom half of table 1.

(ii) *Apparatus and stimuli*

The stimuli were generated by a Macintosh PowerBook G3 portable computer and displayed in the centre of a 14 inch monitor. Participants responded on each trial by pressing either the '.' key or the 'x' key on the keyboard. Each stimulus was composed of a set of coloured dots randomly located on the screen. For the feature trials, one type of trial consisted of pink dots and the other type consisted of blue dots. The configural trials consisted of a mixture of pink and blue dots. For any trial (feature and configural), the total number of dots varied from a minimum of 6 to a maximum of 20 and the spatial position of the dots varied from trial to trial. Thus, the task could not be solved by incidental factors of number or spatial position of dots. In addition, a small proportion of yellow and green dots were added to each stimulus, for both the feature and configural trials. These were added after a pilot study revealed ceiling performance in both children with and without autism using pink and blue dots only. The yellow and green dots were therefore added as distracters in order to increase the overall difficulty of the task, to allow the observation of any differences that might exist between the two groups. The numbers of yellow and green

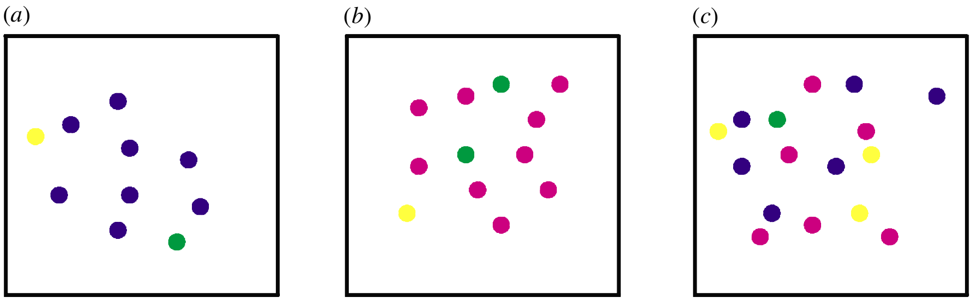

Figure 2. Illustrations of the stimuli presented in feature trials (*a*,*b*) and in configural trials (*c*) in experiment 2. The absolute numbers of dots and their positions on the computer screen were varied across trials. A random number of green and yellow dots were added to each stimulus to increase the overall difficulty of the discrimination.

distracter dots added to each stimulus varied between two and eight (examples of the stimuli used are presented in figure 2).

(iii) *Design and procedure*

Each child in each group was first administered the RSPM followed by the computerized feature–configuration patterning task. Children were shown each trial type (A, B and AB) separately and it was explained that they had to find out which of two keys ('x' or '.') they must press for each stimulus. For each trial type, they were shown that if they pressed the 'correct' key, the computer would display a large tick in the centre of the screen and make a chirping sound, whereas if they pressed the 'incorrect' key, the computer would display a cross and make an 'uh-oh' sound. The children were then given eight practice trials, two trials of A, two of B and four of AB, randomly intermixed. After a short pause (the length depending on the child saying that they were ready) the test trials began. There were 88 trials in total, 44 configural AB trials and 22 feature trials of A and 22 trials of B. Trial types were randomly intermixed. Children were required to complete all 88 trials. For each trial, the stimulus remained on the screen until a response had been made or 6 s had elapsed, whichever was the sooner. Following stimulus offset, feedback was presented in the centre of the screen for 500 ms followed by a 500 ms intertrial interval during which a blank screen was presented. Error data were recorded on each trial.

(b) *Results*

For each child, the average per cent correct for the feature trials was separately calculated from that for the configural trials. The graph in figure 3 shows the average per cent correct scores for the feature and configural trials for the group with autism and typically developing children. The graph indicates that the typically developing children responded more accurately on the configural trials, whereas the children with autism responded more accurately on the feature trials. A mixed ANOVA was conducted on the data, with group as a between-participants factor and trial type (configural and feature) as a within-participants factor. There were no significant main effects but a significant interaction between group and trial type ($F_{1,22} = 16.9$, $p < 0.0006$). Simple effects of this interaction revealed a significant effect of trial type for the typically developing group ($F_{1,22} = 10.75$, $p < 0.003$), confirming that these children performed better on configural than feature trials, and a significant effect of trial type for the group with autism ($F_{1,22} = 6.39$, $p < 0.02$), showing that autistic children performed better on the feature than the configural trials. The difference between the groups on the feature trials marginally failed to reach significance at the 0.05 level ($F_{1,30} = 3.6$, $p = 0.069$). Finally, there was no difference between groups on the configural trials.

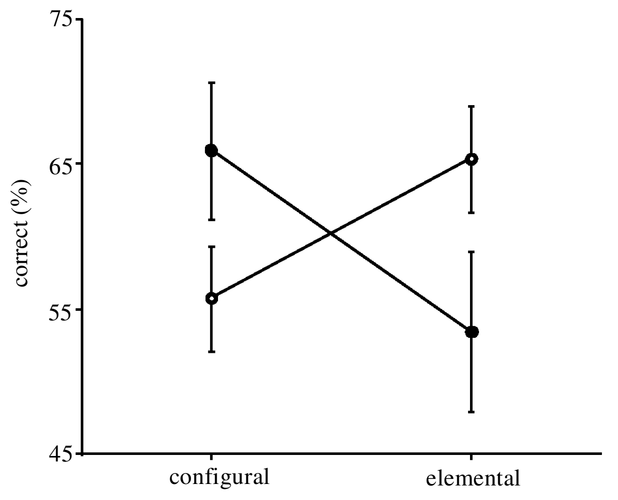

Figure 3. Average per cent correct for each group for configural trials and for feature trials in the feature–configural patterning task in experiment 2. The error bars represent s.e.m. White circles, autistic; black circles, control.

(c) *Discussion*

The pattern of results on the feature–configural patterning task is broadly consistent with that observed in the previous experiment: performance by the group with autism on the feature trials was better than their performance on the configural trials and the two groups did not differ on the configural trials. Rather different from the pattern of results of the previous experiment was the fact that the typically developing group responded more accurately on the configural than on the feature trials. Thus, it might be said that while the group with autism showed a bias towards feature processing, the typically developing group showed a bias towards configural processing. This bias in the typically developing children is not unexpected: the same has been shown in several studies with typical adults (Williams *et al.* 1994; Shanks *et al.* 1998). The weak central coherence hypothesis might account for these patterns by arguing that, while in normal individuals there is a drive for coherence which interfered with performance on feature trials, the lack of this drive in autism resulted in a bias for feature processing, which interfered with processing the configuration of the features on configural trials. The difficulty with this argument is that no difference was observed between groups on the configural trials, indicating that configural processing is not compromised in autism. Instead, the enhanced performance on the feature trials might be accounted for by the hypothesis that the perception of features is particularly acute in autism, but that this perceptual advantage does not interfere with the processing of configurations of features.

The results of the experiments presented so far raise the possibility that some of the effects seen in visual–spatial tasks in autism, such as the superior performance on the embedded figures task, could result from abnormal perceptual processes that enhance the salience of feature representations, rather than the deficient integration processes proposed by the weak central coherence hypothesis. However, in order to fully assess the suggestion that the locus of 'low' level weak central coherence is perceptual processing, we need to conduct studies that assess perception from the very earliest perceptual processes. Very little research has been conducted to assess early visual perceptual processes in autism, such as spatial resolution. However, there have been some preliminary suggestions of enhanced pitch perception in autism (Bonnel 2003). Two of us (J. Alcántara and E. Weisblatt) have begun a programme of experiments systematically to investigate peripheral auditory processing in autism, and one of these studies, on auditory filters, is presented here.

5. AUDITORY-FILTER SHAPES IN HIGH-FUNCTIONING INDIVIDUALS WITH AUTISM OR ASPERGER SYNDROME

There have long been suggestions that abnormalities of sensory processing might be primary in autism but relatively little formal work has been carried out in the auditory domain. In an early study, Goldfarb (1961) studied 'schizophrenic' children, many of whom would now probably be diagnosed with autism. The children had normal auditory thresholds but showed either extreme distress or lack of response to a tone that normal children found noticeable but not aversive. More recently, Myles *et al.* (2000) conducted a survey of 42 children with AS and showed that 71% of the children showed some difficulties with auditory perception, such as hypersensitivity to specific auditory signals.

One of the most commonly reported auditory problems in individuals with autism is an inability to understand speech when background sounds are present. The problem is often quantified in the laboratory by measuring the SNR required to achieve 50% correct identification of speech, referred to as the SRT. In a recent study, Alcántara *et al.* (2003) measured the SRTs of a group of HFA or AS. Participants were required to identify sentences presented in five different background sounds, including a steady speech-shaped noise, a single competing talker, and noises with spectral or temporal dips. The temporal dips arise because there are moments, during brief pauses in speech, for example, when the overall level of the competing speech is low. The spectral dips arise because the spectrum of the target speech is often quite different from that of the background speech, at least over the short term. The individuals with HFA–AS were found to have significantly lower (i.e. worse) SRTs than the age and IQ-matched control participants, particularly for those background sounds that contained temporal dips.

The speech perception problem may be understood in terms of both deficits in central and peripheral levels of processing. For example, the process of detecting speech in background sounds may be viewed as an example of 'auditory scene analysis', whereby information arising from several simultaneous sources is perceptually grouped into separate 'auditory objects' or perceptual streams (Bregman 1990). In other words, the complex sound is analysed into several streams and we choose to attend to one stream at a time. This 'attended' stream then stands out perceptually, while the rest of the sound is less prominent. This is an example of what the Gestalt psychologists called the 'figure–ground phenomenon' (Koffka 1935). Deficits in the perception of speech in noise, as the weak central coherence hypothesis would argue, may therefore result from problems in combining information from the constituent parts to form the 'whole', or using nonauditory information, such as contextual cues, to facilitate speech recognition.

Alternatively, at the peripheral processing level, the process of detecting speech in background sounds may be understood in terms of the 'frequency selectivity' of the auditory system. Frequency selectivity is one of the most basic properties of hearing and refers to our ability to separate or resolve, at least to a limited extent, the components in a complex sound, such as speech. It depends on the filtering that takes place in the cochlea. Specifically, sounds undergo an initial frequency analysis at the level of the BM in which they are decomposed into their constituent frequency components. The BM behaves as if it contained a bank of continuously overlapping bandpass filters, called 'auditory filters'. Each filter is tuned to a particular centre frequency, with the BM responding maximally to that frequency and responding progressively less to frequencies away from the centre frequency. The relative response of the filter, as a function of frequency, is known as the *auditory filter shape*. Thus, masking only occurs when the masking sound produces responses in the auditory filters tuned close to the signal frequency.

The frequency tuning properties of the BM are quantified by measuring the 'shape' of the auditory filter (Patterson & Moore 1986). This is a physically defined measure of the sharpness of tuning at a given BM location and describes the frequency selectivity of the peripheral auditory system. In normal hearing individuals, the action of a physiological 'active process' (Ruggero 1992) markedly influences the degree of frequency selectivity present. Thus, in normal hearing participants the auditory filters are relatively sharp, and have BWs of *ca.* 10–12% of the centre frequency of the filter (Moore & Glasberg 1981). In hearing-impaired individuals, the active process is often reduced or absent, resulting in frequency tuning properties that are significantly worse than those measured in individuals with normal hearing (Ruggero *et al.* 1996): auditory filters are often two to three times as wide as normal (Glasberg & Moore 1986).

The role of frequency selectivity in speech-in-noise perception is best illustrated by studies using hearing-impaired individuals who also report particular difficulty understanding speech in the presence of background sounds. This is the case even when the speech is presented at a high level, so that it is above their absolute hearing threshold and audibility is not a factor. The relatively poor performance of hearing-impaired people appears to arise partly from a decrease in frequency selectivity. One of the perceptual consequences of a decrease in frequency selectivity is a greater susceptibility to masking by interfering sounds: when we try to detect a sinusoidal signal in a noisy background, we use the auditory filter that gives the best SNR. When the auditory filters are relatively narrow, as is the case for normal hearing individuals, most of the background noise is attenuated as it falls outside the passband of the auditory filter centred on the signal frequency. In an impaired ear, this same filter passes much more of the noise, as it is wider, especially on its low-frequency side, making it harder to hear the signal. This is generally known as 'upward spread of masking', and results in a marked susceptibility to masking by low-frequency sounds, such as car noise and air-conditioning noise.

Accordingly, the aim of the current study was to measure frequency selectivity for a group of individuals with HFA or AS. This was done in order to determine whether abnormalities in the peripheral processing of auditory stimuli are responsible for the observed difficulties in speech-in-noise perception, or whether, as predicted by the weak central coherence hypothesis, they result from post-perceptual processes such as grouping and integration. We measured the auditory filter shapes of eight individuals using a masking experimental paradigm. Masking experiments may be used to explore the limitations in frequency selectivity of the auditory system in the following way: it is a matter of everyday experience that one sound may be rendered inaudible in the presence of other sounds. For example, if a signal to be detected and a masking sound are widely different in frequency, then the signal will generally be heard. If the signal and masker are close in frequency, then masking is more likely to occur. Thus, masking reflects the limits of frequency selectivity: if the selectivity of the ear is insufficient to separate the signal and the masker, then masking occurs.

In order to determine the auditory filter shape, we measured the threshold for a 2 kHz sinusoidal tone signal in the presence of a masker whose frequency content is varied in a systematic way. We used the notched-noise method of Patterson (1976), which ensures that the listener always listened through the auditory filter centred at the signal frequency. The experiment is illustrated schematically in figure 4 (taken from Moore 1997). The masker is a noise whose spectrum has a notch centred at the signal frequency. The deviation of each edge of the notch from the centre frequency is denoted by Δf. The width of the notch is varied, and the threshold of the signal is determined as a function of the notch width. For a signal symmetrically placed in the notched noise, the highest signal-to-masker ratio will be achieved with the auditory filter centred at the signal frequency, as illustrated in figure 4. As the width of the notch in the noise is increased, less and less noise will pass through the auditory filter. Thus, the threshold of the signal will drop. The amount of noise passing through the auditory filter is proportional to the area under the filter covered by the noise. This is shown as the shaded areas in figure 4. If we assume that threshold corresponds to a constant signal-to-masker ratio at the output of the auditory filter, then the change in signal threshold with notch width tells us how the area under the filter varies with Δf. By differentiating the function-relating threshold to Δf, the shape of the auditory filter is obtained. In other words, the slope of the function-relating threshold to Δf for a given deviation Δf is equal to the 'height' of the auditory filter, at that value of Δf. If the threshold decreases rapidly with increasing notch width, this indicates a sharply tuned filter. If the threshold decreases slowly with increasing notch width, this indicates a broadly tuned filter. An example of an auditory filter shape obtained using this method is shown in figure 5. It should be noted, however, that although the derivation is based on the use of linear power units, the relative response of the filter is usually plotted on a decibel scale, as in figure 5. The response of the filter at its centre frequency is arbitrarily defined as 0 dB, meaning that the output magnitude is equal to the input magnitude for a signal at the centre of the frequency. For signals with frequencies above and below the centre frequency of the filter, the output magnitude is less than the input magnitude, hence the negative decibel value, meaning that the signal level is attenuated when it is filtered.

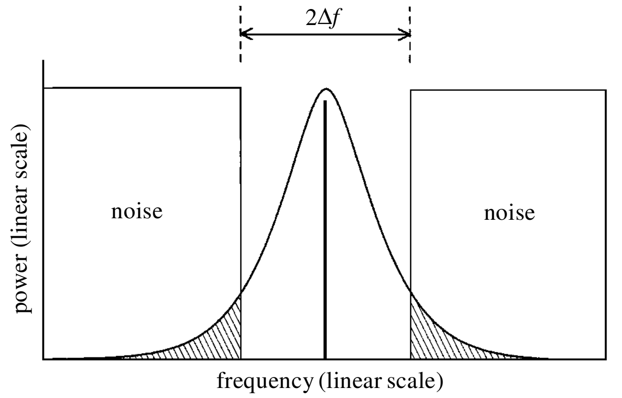

Figure 4. Schematic illustration of the notched-noise technique used by Patterson (1976) to derive the shape of the auditory filter. The threshold of the sinusoidal signal is measured as a function of the width of the spectral notch in the noise masker, which has an overall width of $2\Delta f$. The amount of noise passing through a filter centred at the signal frequency is proportional to the area of the shaded regions (taken from Moore 1997).

(a) *Methods*

(i) *Stimuli*

The masker comprised two noise bands symmetrically placed about the signal frequency of 2 kHz. The spectrum level of the noise was 40 dB SPL. Each noise band was 800 Hz wide at the 3 dB down points (equivalent to a 50% reduction in power). The deviation from the signal frequency (f_0) to the edges of the notch of each noise band, expressed as $\Delta f/f_0$, was 0.0, 0.1, 0.2 or 0.3. That is, notch widths (Δf) of 0, 200, 400 or 600 Hz were used to separate the two noise bands. On each trial, two bursts of noise were presented, separated by a silent interval of 500 ms.

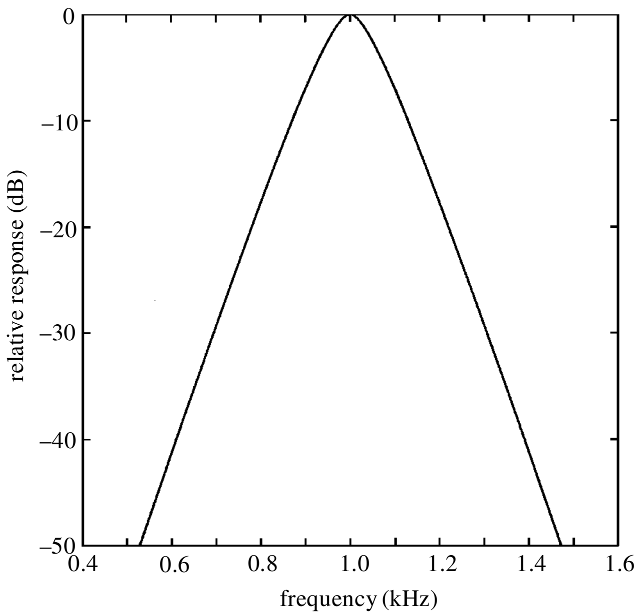

Figure 5. An example of an auditory filter shape obtained using the notched-noise method. The filter has a centre frequency of 1 kHz. The filter response is plotted relative to the response at the tip, which is arbitrarily defined as 0 dB.

The noise burst had a 200 ms steady-state portion and 10 ms cosine-shaped rise–fall times. The signal was turned on at the same time as either the first or second of the noise bursts, the choice being selected at random. The stimuli were generated exactly as described in Glasberg *et al.* (1984) and were recorded onto a CD. They were replayed through a Marantz CD player attached to a NAD (New Acoustic Dimension) power amplifier, and the left earphone of a Sennheiser HD414 headset.

(ii) *Participants*

Eight HFA–AS took part in the study. All had normal hearing thresholds (<20 dB hearing loss) across the audiometric frequencies (0.25–8 kHz) and middle-ear function within normal limits, and were paid for their services. Participants were clinically diagnosed according to the criteria specified by DSM-IV (American Psychiatric Association 1994). The mean age of the participants was 18 years 3 months (range 13–28 years).

(iii) *Procedure*

Signal thresholds, determined using a two-interval forced-choice task, were used to estimate the psychometric functions for each notch width. Participants were required to mark on a score sheet whether the signal occurred in the first or second interval of each test trial. Feedback was not provided. The 2 kHz signal was presented at four levels covering a 12 dB range in 4 dB steps for each notch width. The highest levels used were 71, 68, 55 and 46 dB SPL, for notch widths of 0.0, 0.1, 0.2 and 0.3, respectively. Participants were first given practice on the task, using between 40 and 80 trials, at a notch width of 0.0, before the formal testing began. Forty trials were then presented at each signal level. They were given a brief rest between each block of 40 trials. Thresholds, defined as the signal levels corresponding to 75% correct, were determined by interpolation. Testing was carried out in a quiet but not sound-attenuating room. Thresholds in the notched noise were at least 20 dB above the threshold that would be imposed by the background noise in the room.

(iv) *Analysis*

It has been found empirically that the shape of the auditory filter can be well approximated by a simple expression, based on the form of a exponential with a rounded top (i.e. the 'roex' model of Patterson *et al.* 1982). In this expression, frequency is described relative to the centre frequency of the filter, by introducing the variable g, which is defined as the deviation from the centre frequency of the filter, divided by the centre frequency (i.e. $g = \Delta f/f$). The shape of the auditory filter, as a function of g, that is, $W(g)$, is therefore approximated by

$$W(g) = (1 + pg)\,e^{-pg}, \tag{5.1}$$

where the variable p is a parameter that determines the degree of frequency selectivity, or sharpness, of the filter. The value of p, which varies from one individual to another, was derived by fitting the integral of equation (5.1) to the data-relating threshold to notch width (see Patterson *et al.* (1982) for full details). The fitting procedure also gives values for the parameter K, which is a measure of the 'efficiency' of the detection process following the auditory filter. Here, K is expressed in terms of the SNR at the output of the auditory filter required to achieve the threshold criterion.

A bandpass filter is often characterized by its BW, which is a measure of the effective range of frequencies passed by the filter. The filter BW is often defined as the difference between the two frequencies at which the response of the filter has fallen by half in power units (i.e. by 3 dB) relative to the peak response. This is commonly known as the *half-power* BW or *3 dB down* BW. For example, if a filter has its peak response at 2000 Hz, and the response at 1900 and 2100 Hz is 3 dB less than the response at 2000 Hz, then it is said to have a BW of 200 Hz. In general, the smaller the BW value, the sharper the filters and the better the frequency selectivity. An alternative measure of BW commonly used is the ERB. The ERB of a filter is equal to the BW of a rectangular filter (i.e. a filter with a flat top and vertical edges) that has been scaled to have the same maximum height and area as that of the specified filter. The ERB of the auditory filter may be easily determined from the results of the notched-noise data as it is equal to $4/p$ multiplied by the centre frequency of the filter.

(b) *Results*

The roex (p) model gave reasonable fits to the data collected: averaged across the eight participants, the root-mean-square deviation of the data from the fitted values was 4.1 dB. The mean value of p was 22.6 with a s.d. of 4.1. The mean value of the ERB was 365 Hz with a s.d. of 72 Hz. The value of K, the 'efficiency' parameter, has a mean of −1.6 dB and a s.d. of 2.3 dB. According to the model, the mean signal threshold for a notch width of 0.0 should be equal to the sum of the noise spectrum level (40 dB), 10 log (ERB) (25.5 dB) and K (−1.6 dB), that is, 63.9 dB. The actual measured value of 62.9 dB (s.d. = 1.4 dB) was in close agreement with the predicted

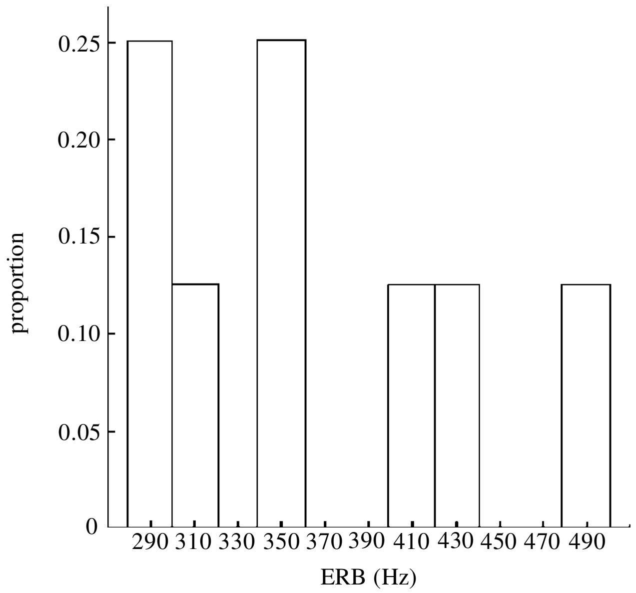

Figure 6. The distribution of auditory filter BWs (ERBs) measured for the individuals with autism. The ERBs have been grouped into bins 20 Hz wide, and the figure shows the proportion of ERBs falling in each bin.

value. Figure 6 shows the distribution of auditory filter BWs (ERBs) measured for the eight HFA–AS subjects. The ERBs have been grouped into bins 20 Hz wide, and the figure shows the proportion of ERBs falling in each bin.

The results for the HFA–AS subjects were compared with those of normal hearing subjects without autism, measured previously by Moore (1987). The subjects used in Moore (1987) were 93 undergraduates at Cambridge University, aged 19–21. No attempt was made to match our subjects with those of Moore (1987), on the basis of IQ or age; therefore, the subjects cannot strictly be treated as controls, and comparisons with our data should be treated with due caution. However, exactly the same procedure was used for both subject groups for the measurement of the auditory filter shapes, and testing was carried out under very similar conditions. Therefore, we believe there is some value in comparing the results of both groups. The mean ERB for the subjects of Moore (1987) was 308 Hz, with a s.d. of 32 Hz. The mean value of K was –0.7 dB with a s.d. of 1.9 dB. A nonparametric analogue of the one-way ANOVA (i.e. the Kruskal–Wallis test) was performed in order to determine if the ERBs measured for the HFA–AS subjects were significantly higher than those of Moore (1987). This test was used as it was not reasonable to assume a particular form of the distribution for the subject populations; however, the data are quantitative and therefore could be ranked. The value of the H statistic was 6.88, so we can reject the null hypothesis that there is no significant difference in the ERB values of both subject groups with a probability level of $p = 0.009$.

(c) *Discussion*

The objective of the current study was to determine the frequency selectivity abilities of a group of HFA or AS. This was achieved by measuring the width of the auditory filter centred at 2 kHz, specifically the ERB, specified in hertz. The mean ERB, as calculated using the roex (p) model of Patterson (1976), was 365 Hz (s.d. = 72 Hz). The mean SNR required for signal detection (K) was –1.6 dB (s.d. = 2.3 dB). As only data for a centre frequency of 2 kHz are reported, and there was a relatively large degree of inter-subject variability in our ERB estimates (s.d. = 72 Hz; see also figure 6), the results of the current study should be treated as preliminary data only.

The mean ERB for our eight subjects was significantly larger than that reported by Moore (1987), for normal hearing university students. In other words, the frequency selectivity of the HFA–AS individuals was worse than for individuals without autism. It is unlikely that the difference in ERBs measured for our participants and those of Moore (1987) was due to a lack of concentration or an inability to perform the psychophysical task on the part of the HFA–AS participants. This is because the value of K measured for our participants was quite small (–1.6 dB), indicating an efficient detection process following auditory filtering, and that the participants were concentrating during the task. In the fitting process, K is an additive constant that adjusts the mean of the fitted values to the mean of the threshold data, both in decibels. Therefore, if our participants' threshold data were, at every point, say 3 dB higher than those of control participants, indicating a lack of concentration or application to the task, the value of K for the autistic participants would be 3 dB higher than that of the controls. In fact, the value of K was negative and very similar to that estimated for control participants who were highly motivated (Patterson *et al.* 1982).

One of the perceptual consequences of having wider than normal auditory filters is a greater susceptibility to masking by interfering sounds, as the auditory filters, centred on a signal, also pass a relatively large amount of noise along with the signal. This may explain why subjects with autism or AS commonly report problems understanding speech when there is background noise also present, as described in § 1. The current results are also consistent with the findings of Alcántara *et al.* (2003), who found that subjects with autism performed significantly worse on speech recognition tasks when there was background noise simultaneously present, than did age- and IQ-matched control subjects. However, Alcántara *et al.* (2003) also found that the subjects with autism were significantly worse at making use of temporal dips present in the background noise. This may indicate that there is also a problem in the integration of information presented over successive time intervals, and consequently a failure to perceptually group information from several simultaneously presented sources into separate 'auditory objects' (e.g. speech and noise). However, the results of the current study indicate that the difficulty encountered by individuals with autism or AS, to perceive speech in noise, can be at least partially explained on the basis of deficits occurring in processing at the level of the auditory periphery.

6. GENERAL DISCUSSION

The general aim of the experiments reported here was to investigate the possible locus of apparent weak central coherence in individuals with autism. With respect to visual processing, it was proposed that individuals with autism might experience difficulty in the formation of a configuration of features, the significance of which differs from when its constituent features are presented alone or in another configuration with other features. However, on the basis of previous experiments that indicate enhanced feature processing but not at the expense of global processing, it was also suggested that the formation of configural representations in autism may be normal, but that their performance on tasks based on feature information may be superior. This was confirmed in two experiments comparing configural and feature processing. These findings are consistent with the proposal that perceptual processing in autism is abnormal in such a way as to enhance the salience of individual perceptual features, but that this does not impact on post-perceptual processes responsible for integrating perceptual information to form a configural representation.

This raises the question of how perceptual processing might result in the abnormally acute representation of feature information. The most rational approach to this question would be to assess perceptual processing in its very earliest stages. This was accomplished here by measuring the auditory filter shapes of individuals with autism, an assessment of peripheral auditory processing on the BM. Contrary to the perceptual hypothesis that we have proposed, which predicts that autistic individuals might show greater than normal auditory frequency selectivity, the auditory filters of individuals with autism were found to be broader than has been found for typical individuals. It seems more than reasonable to suppose that such early auditory analysis in the cochlea would have an important impact on later stages of auditory perception. Indeed, the abnormally broad auditory filters observed here could account for the difficulty of detecting speech in noise observed in individuals with autism by Alcántara *et al.* (2003).

However, at first glance, such a finding does not appear to be consistent with the proposal that perceptual processing results in particularly acute representations of stimulus features. At this point, we can only speculate about why. One possibility is that acute feature representation may be specific to the visual modality. This seems highly unlikely, since there are studies that show enhanced feature processing in the auditory domain (Heaton *et al.* 1998; Mottron *et al.* 2000). A second possibility is that abnormalities in the earliest stages of perceptual processing, such as those observed here, do not impact adversely on all later perceptual processes. Intriguingly, although hearing-impaired individuals show auditory filters two to three times as wide as those of the normally hearing population (and have difficulties hearing speech in noise), these individuals do not necessarily show deficits in pitch perception and frequency discrimination (Moore *et al.* 1995). A third possibility is that the abnormalities that produce the enhancement of feature processing in autism may occur later in the formation of perceptual representations. This possibility assumes that the relationship between the product of peripheral perceptual processing and the nature of the consequent perceptual representation is not straightforward.

Alternatively, we may need to appeal to abnormalities in post-perceptual stimulus processes to explain enhanced feature processing in autism. There are, for example, cortical mechanisms that could modify the salience of perceptual representations by changes in the SNR. For example, it is known that the anticholinergic drug, scopolamine, impairs visual and auditory signal detection (Warburton 1977), and cortical cholinergic lesions impair the detection of feature stimuli in the environment (Robbins *et al.* 1989). These findings indicate that one important function of the central cholinergic system is the enhancement of stimulus processing at the cortical level, in effect a cortical system that modulates attention to feature stimuli. These studies therefore raise the possibility that enhanced feature processing in autism may be a consequence of abnormal cortical arousal systems, such as enhanced cholinergic activity which increases feature detectability, and suggest new avenues of investigation of abnormal stimulus processing in autism at the neural level.

Finally, the possibility that the salience of perceptual representations of features can be altered would be usefully investigated in connectionist models that could attempt to model data such as those obtained in the configural learning experiments presented here by modifying different parameters that have the effect of raising the salience of features in an information processing task. It is hoped that further studies of peripheral perceptual processes, central cortical processes and computational studies will allow us to identify the mechanisms underlying the abnormalities in stimulus processing associated with autism spectrum disorders.

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GLOSSARY

ANOVA: analysis of variance
AS: Asperger syndrome
BM: basilar membrane
BW: bandwidth
CA: chronological age
ERB: equivalent rectangular bandwidth
HFA: high-functioning individuals with autism
RSPM: Raven's Standard Progressive Matrix
SNR: signal-to-noise ratio
SPL: sound pressure level
SRT: speech reception threshold