



PERGAMON

Neuroscience and Biobehavioral Reviews 25 (2001) 287–295

NEUROSCIENCE AND
BIOBEHAVIORAL
REVIEWS

www.elsevier.com/locate/neubiorev

Review

Imitation, mirror neurons and autism

J.H.G. Williams^{a,*}, A. Whiten^b, T. Suddendorf^c, D.I. Perrett^b

^aDepartment of Child Health, University of Aberdeen, Foresterhill, Aberdeen AB25 2ZD, UK

^bDepartment of Psychology, School of Psychology, University of St. Andrews, St. Andrews, Fife KY16 9JU, UK

^cSchool of Psychology, University of Queensland, Brisbane, Old 4072, Australia

Received November 2000; revised 8 March 2001; accepted 19 March 2001

Abstract

Various deficits in the cognitive functioning of people with autism have been documented in recent years but these provide only partial explanations for the condition. We focus instead on an imitative disturbance involving difficulties both in copying actions and in inhibiting more stereotyped mimicking, such as echolalia. A candidate for the neural basis of this disturbance may be found in a recently discovered class of neurons in frontal cortex, ‘mirror neurons’ (MNs). These neurons show activity in relation both to specific actions performed by self and matching actions performed by others, providing a potential bridge between minds. MN systems exist in primates without imitative and ‘theory of mind’ abilities and we suggest that in order for them to have become utilized to perform social cognitive functions, sophisticated cortical neuronal systems have evolved in which MNs function as key elements. Early developmental failures of MN systems are likely to result in a consequent cascade of developmental impairments characterised by the clinical syndrome of autism. Crown Copyright © 2001 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Imitation; Mirror neurons; Autism; ‘Theory of mind’

Contents

1. Introduction: the basis of autism 287
2. The role of early imitation 288
3. Imitation in autism 289
4. Neurobiology of imitation 289
5. The functional significance of mirror neurons 290
5.1. Speech 290
5.2. Theory of mind 290
5.3. More basic intersubjective phenomena: emotional contagion and shared attention 290
5.4. Imitation 291
6. Mirror neurons and autism 291
7. Autism, executive functions and mirror neurons 291
8. Neuroimaging mirror neurons and ‘theory of mind’ 292
9. Testing the hypothesis 292
10. Conclusion 293
References 293

1. Introduction: the basis of autism

The autistic spectrum disorders are increasingly being recognised as an important cause of social disability [1]

and have been the focus of a flurry of research in the last decade [2–5]. Here, we suggest that juxtaposing some of these psychological findings with recent discoveries in neurobiology offers the prospect of a new and potentially powerful model of both early social functioning and the disorders in it that are associated with autism.

The autistic spectrum disorders are characterised by impairments in social interaction, imaginative ability and

* Corresponding author. Tel.: +44-1224-552-471; fax: +44-1224-663-658.

E-mail address: justin.williams@abdn.ac.uk (J.H.G. Williams).

repetitive and restricted patterns of behaviour. In those children with autism as opposed to Asperger's syndrome, the disorder has an onset before the age of 3 years and is associated with delayed and abnormal language development [6–8]. The condition is heterogeneous, both with respect to cause and clinical picture. It may be associated with abnormalities such as epilepsy, mental handicap and various brain pathologies. There is also evidence that autism is part of a broader phenotype [9] and sub-syndromal symptoms are often found in population surveys [1]. As such, it may be best conceptualised as a dimensional rather than a categorical disorder [10]. The distinction between autism and Asperger's syndrome is also subject to diverse opinions. Happe [11] concludes that for most researchers 'Asperger's syndrome is a label for high-functioning autistic individuals'. This distinction was supported recently in a cluster analysis by Prior et al. [12]. Perhaps due to this diverse and complex clinical picture, no common underlying mechanism has yet been identified. It is clear, however, that autism is a developmental disorder characterised by a cascade of specific impairments over the course of development.

Baron-Cohen et al. [13] demonstrated that children with autism typically had special difficulties in understanding the beliefs of others and suggested that they lacked the 'theory of mind' ('ToM') necessary to pass such tests. This claim has since been supported by a wealth of experimental investigations and has led some to argue that at the root of autism is a ToM deficit or delay [14–16]. However, a metarepresentational ToM deficit seems unsatisfactory as a primary explanation for autism. First, ToM as tested by Baron-Cohen et al. [13] does not typically become at all robust in normal children until after the fourth year, yet autistic disorders are manifested earlier. This has led researchers attracted to ToM explanations of autism to a search for 'precursors' to ToM, which might be apparent in early autistic disorders. Candidates for such precursors include pretend play [17] and a capacity to engage in shared attention with another individual [18]. Second, clinicians have argued that early social deficits are often broader in scope than implied by the focus on ToM [19]; Hobson [20] for example, has argued that the primary deficit is more aptly described as socio-affective, characterised by a lack of empathic and emotional engagement with others. The third and final problem is that autism is often characterised by other social and non-social problems that appear ill-accommodated by a primary ToM deficit. These include repetitive and stereotyped behaviour (including copied behaviours), obsessive desire for sameness, delayed and deviant language development (including echolalia) and difficulties in perceiving or planning at high-levels of organisation ('executive function' [4]). The challenge in understanding autism, then, is to identify dysfunction in underlying mechanisms that can account for a wider range of symptoms than the ToM or executive function theories alone, thus explaining clustering of symptoms in the autistic spectrum disorders. It does not necessarily include accounting for those characteristics which are

not specific to the condition such as global developmental delay, aggression or sleep disturbance.

2. The role of early imitation

The possibility that deficits in imitation might be particularly intimately connected with the earliest developmental stages of autism was first set out systematically by Rogers and Pennington [21]. According to these authors, imitation might fill at least two of the three gaps left by the ToM explanation noted above: first, imitation has characteristics suggesting that the mechanisms underlying it could be precursors (perhaps the first that can be identified in infancy) to full ToM; and second, imitation may also be fundamental to the other, broader kinds of social deficits seen in autism. The relationship between imitation and the third group of (largely non-social) deficits listed above is one we shall discuss once other parts of our model have been explained. Rogers and Pennington [21] collated existing empirical evidence of imitation deficits in autism, which we discuss in the following section. First, however, some key theoretical bases for a link between imitation mechanisms and later-developing ToM need to be recognised.

Imitation and the attribution of mental states bear some fundamental resemblances [22,23]. Both involve translating from the perspective of another individual to oneself. Thus in accurately reading the belief of another, one essentially copies the belief into one's own brain, creating a 'second-order' representation of the other's primary representation of the world (and, of course, not confusing it with one's own beliefs, at least in the normal case). Conversely, in imitating, one must convert an action plan originating from the other's perspective into one's own. A more specific linkage between imitation and ToM is implied by the fact that one of the two principal models of how ToM operates is designated the 'simulation' theory [24]. Its rival is the 'theory theory', which sees the child acting somewhat like a young scientist, observing patterns of behaviour in others, and developing theories about mental states to explain and predict them. The simulation theory instead proposes that children come to read minds by 'putting themselves in the other's shoes', and using their own minds to simulate the mental processes that are likely to be operating in the other. 'Acting as if you are the other'—simulation—is thus at the covert, mental level akin to what is involved at the overt level in imitation. Current views include the possibility that both 'simulation theory' and 'theory-theory' processes are at work in the human case [25].

Meltzoff and Gopnik [26] reviewed evidence for imitation in the earliest phase of infancy and proposed that this could provide a key starting-state for the development of ToM. The nub of their hypothesis is that the new-born's capacity to translate between the seen behaviour of others and what it is like to perform that same behaviour offers a

crucial basis for recognising the linkage between mental states and actions.

There are, thus, substantial theoretical reasons for considering imitation as a prime candidate for the building of a ToM. Rogers and Pennington's theory [21] was that at the root of autism is 'impaired formation/co-ordination of specific self-other representations', manifest first in impaired imitation, followed by a cascade of impairments in emotion-sharing, joint attention and pretend play (thus including the broad range of social deficits), and ToM. What, then, is the evidence for imitation being affected in autism?

3. Imitation in autism

Evidence for an imitative deficit in autism has been reviewed elsewhere [21,27–29]. None of these reviews is comprehensive, but together they cite 21 experimental studies of the imitative competence of individuals with autism. The studies have been heterogeneous with respect to the mental ages tested, the types of control groups used and the imitation tests themselves, but only two studies did not find an imitative deficit in the autistic samples and then possibly because of the simplicity of the tasks, leading to ceiling effects. Smith and Bryson [27] conclude that the literature shows a 'consistent finding that people with autism do not readily imitate the actions of others'. Furthermore it is worth noting the magnitude of the imitative deficit. For instance, Rogers et al. [30] detected group differences of approximately 1.5 standard deviations between the autistic and control group means. More recently, Hobson and Lee [31] found that only 1 out of 16 (6%) subjects imitated the style of one of their tasks, compared to 12 out of 16 (75%) controls. A number of studies have detected significant group differences with just 10 subjects per group. The magnitude of this deficit then can be at least as great if not greater than the 'theory of mind' deficit. Rogers [28] additionally notes the difficulties faced by carers in intensively teaching imitation to young children with autism. Deficits in the imitation of 'symbolic' elements (such as pantomiming brushing one's teeth with a non-existent toothbrush) might be expected in view of the diagnostic criteria; thus of special interest are those concerning basic body movements or gestures. These were first demonstrated by DeMeyer et al. [32] and have since been replicated in at least nine further studies [27–29]. Rogers [28] concludes that 'every methodologically rigorous study so far published has found an autism-specific deficit in motor imitation'. The conclusion that the imitative deficit may be operating at such a fundamental level is important to our synthesis with neurobiological findings discussed further below.

The reason for difficulties in imitation associated with autism remains unclear but some clues may come from an examination of the type of imitative deficit present. Firstly, imitation of meaningless gestures would appear to be

affected more than imitations of actions with objects [30]. Perhaps the use of objects in some tests may offer a 'prop', helping to shape a matching response; by contrast, difficulties in copying raw gestures underlines the more basic nature of the imitative deficit referred to earlier [33]. Secondly, when children with autism were asked to imitate an unconventional action with a common object (such as drinking from a teapot) they were more likely to make errors [27]. This again provides evidence for an imitative deficit more fundamental than that expected on the basis of other known impairments. Thirdly are reversal errors [27,29]; for example, in 'copying' the action of holding the hands up palm away, grasping the thumb of one hand with the other hand, autistic subjects tended to hold their palm towards themselves, re-creating the hand view they had seen (sometimes also failing to grasp the thumb) instead of translating the perspective the other had seen [25]. Finally there are greater group differences with respect to sequences of actions than when single actions alone are being imitated [30]. Together, these kinds of errors suggest that deficits may be occurring in the basic ability to map actions of others onto an imitative match by oneself [29] especially when such actions are complex.

Finally, there is a curious aspect of imitation-like phenomena in relation to autism, that concerns the well-known repetitive and stereotyped behaviours and speech that may occur. These may be copied from others, including words and phrases (echolalia) and sometimes actions, that are mimicked without regard to their normal goals and meanings. At first sight these phenomena seem contradictory to the notion of an imitative deficit, but they may instead offer clues to the underlying neural dysfunction. We will discuss this in a later section, in integration with the findings on neurobiology to which we now turn.

4. Neurobiology of imitation

Patients with left frontal lobe lesions may show imitative dyspraxia [33,34]. These patients are unable to repeat actions performed by others, despite demonstrating adequate motor control of their limbs. Furthermore, they are unable to replicate such gestures on a manikin [35]. This is consistent with the idea that imitation may normally rely on representation of action at a 'supramodal' level [36], which is unavailable to these patients; the same lesion site will accordingly disrupt the replication of a gesture whether on the self or on another body.

Work at the neuronal level in non-human primates has started to indicate the pathways by which representation of such actions may be built up. A number of different types of specialised neuron have been identified in the superior temporal sulcus (STS) of monkeys that are dedicated to visual processing of information about the actions of others. Particular populations of cells code the posture or the movements of the face, limbs or whole body [37–41]. Other

classes of neurons appear to code movements as goal-directed actions and are sensitive to hand and body movements relative to objects or goals of the movements (e.g. reaching for, manipulating or tearing an object) [42–45].

Of special relevance to our model is a subset of such action-coding neurons identified in the prefrontal cortex (area F5) in monkeys [46,47]. Such neurons will fire when the monkey performs a specific action, such as a precision grip, but also when an equivalent action (a precision grip, in this example) is performed by an individual the monkey is watching. These have been called ‘mirror neurons’ (MNs) [47]. Their potential relevance to imitation is signalled by another label: ‘monkey see, monkey do’ neurons [48]. F5 cell activity, however, does not automatically lead to motor responses and action performance, otherwise seeing actions performed would lead to obligatory copying (echopraxia). The execution of actions when F5 cells are activated by the sight of actions of others, may be inhibited by mechanisms operating elsewhere in the motor pathway [49] and perhaps involving orbitofrontal cortex [50].

Although MNs cannot be studied directly in the same way in humans, the existence of a system with the properties of MNs is supported by ingenious alternative approaches [47,51] including the use of transcranial magnetic stimulation (TMS) of human motor cortex to produce electromyographic potentials in muscle groups [52]. Observing actions involving distal finger movements but not proximal whole arm movements selectively lowered the threshold for TMS to induce electromyographic activity in distal musculature. This demonstrates input from the sight of movements to the neural system involved in motor control of the same movements.

Several functional imaging studies have noted that the sight of hand actions produces activity in frontal regions (premotor cortex and Broca’s area) [53,54], which may be homologous to F5 in the monkey [49]. In a recent fMRI study, activation of the left Broca’s area during observation of finger movements became more intense when that same action was executed simultaneously [55]. These imaging studies also reveal activity in parietal cortex. This area, along with possibly the superior temporal sulcus, also shows some evidence of mirror neuron activity ([56] and M. Iacoboni (pers. com.)).

5. The functional significance of mirror neurons

MNs appear to have the capacity to embody a ‘supramodal representation’ of action, functioning as a bridge between higher visual processing areas and motor cortex (between seeing and doing). As yet, MNs have been investigated with respect to hand actions, but it seems likely that others are concerned with different actions, such as facial expression and speech, and perhaps eye movements and the higher-level abstractions [41,42]. However, MNs have only recently been discovered. Their precise significance is not

yet known, but some specific suggestions are particularly relevant to our discussion.

5.1. Speech

Rizzolatti and Arbib [49] have suggested that the part of the monkey brain which contains MNs dealing with hand actions has evolved to subserve speech in humans, with language building on top of a ‘prelinguistic grammar of actions’ already existing in the primate brain. By acting as a bridge between perceived and performed action and speech, the MN system is thus suggested to have provided the foundations for the evolution of dialogue. Furthermore, if MNs do process auditory representations as they do visual ones, they may be important in representing the relationships between words and their speaker like the personal pronouns. If this is true, the MN system may also provide crucial foundations ontogenetically, particularly with respect to the development of the pragmatic aspects of speech, and thence more complex aspects of language. However, not only the pragmatics of speech may depend on a functional mirror neuron system. Lack of invariance in the physical structure of phonemes gave rise to the motor theory of speech perception, which suggests that we hear sounds according to how we produce them [57,58]. If MNs are an important link between the production and perception of speech—or between sender and receiver [49]—then an intact MN system may be important for other stages of language development as well.

5.2. Theory of mind

Gallese and Goldman [59] have suggested that it may be possible to predict and also ‘retrodict’ an observed person’s mental state by constructing the appropriate mental correlates of an act once it is ‘reconstituted’ in the observer’s own MN system. They suggest that MN activation can permit the generation of an executive plan to perform an action like the one being watched, thereby getting the observer ‘into the mental shoes’ of the observed (but see also Gallese [60]). They also note this is a process that requires an ability for controlled inhibition to prevent concomitant execution of an observed action. They argue that such a mechanism is in keeping with the ‘simulation’ model of ToM, which also requires that observed action sequences are represented in the observer ‘off-line’ to prevent automatic copying, as well as to facilitate further processing of this high-level social information.

5.3. More basic intersubjective phenomena: emotional contagion and shared attention

Before moving on to consider the possible role of mirror neurons in autism, it is important to note that there seems no reason in principle why MNs should not address a wide range of actions and the mental states they connote. For example, since emotional states are closely linked to certain facial expressions, observation of a facial expression might

result in mirrored (but mainly inhibited) pre-motor activation in the observer and a corresponding ‘retrodicted’ emotional state. Such a process might help to explain the phenomenon of emotional contagion, in which people automatically mirror the postures and moods of others [61]. This seems particularly likely in view of the close connections between STS neurons, the mirror neuron circuits and the amygdala [43]. Indeed, there is direct electromyographic evidence that observers adopt facial muscle activity congruent with expressions witnessed even when this process is not at an overt level [62].

Like emotion reading [20], a capacity for shared attention has been proposed as an important precursor to full theory of mind, partly on the basis of evidence that deficits in this capacity are apparent early in the life of individuals with autism, their occurrence thus being explored as an early warning sign [16,63,64]. Here we note simply that being able to identify the focus of attention of another, or to be able to consider drawing their attention to the focus of one’s own attention, is another case of being able to ‘stand in the other’s shoes’. In shared attention, each individual’s attentional focus mirrors the other, raising the prospect that MNs could play a role in this achievement.

5.4. Imitation

In discussing the possible role of MNs in each of the above capacities, some references to imitative-like phenomena (‘standing in the others shoes’) have been made. It might be thought that the obvious functional role of MNs would indeed lie in imitation (in which case MN outputs would *not* be inhibited). However, noting that there is little evidence of imitation in monkeys [65,66] Gallese and Goldman [59] suggested that in the monkeys in which they have been identified, MNs are functioning to facilitate social understanding of others (to the extent the monkey ‘stands in the same ‘mental shoes’ as the other, as Gallese and Goldman put it). This is not argued to amount to ToM (for which there is also little evidence in monkeys [22,23]), but it may nevertheless represent the kind of foundation which permitted the evolution of ToM in humans [59].

However, we note there is better evidence for imitation in apes than in monkeys, and of course imitation is both evident and functionally important in our own species [66,67]. We suggest that the evolution of imitation in humans is likely to have utilised an existing MN system, even if its prior uses lay in more generalised kinds of social understanding. As mentioned earlier, fMRI with human subjects during a simple imitation task did indeed find activation in area 44 as well as in parietal cortex, suggesting that the MN system is involved in imitation in humans.

If Gallese and Goldman are right about the function of MNs in monkeys, certain additional capacities had to evolve before MNs could support either imitative or more advanced ToM functions. We may guess that these additional factors reflect the increased cortical volumes of great apes and humans and

the representational capacities associated with them; their precise nature is a question for future research. For now, the critical hypothesis is that MNs provide a key foundation for the building of imitative and mindreading competencies. Accordingly, if Rogers and Pennington were right about the linkage between imitation and ToM, we should, thus, expect that MNs play important roles in the whole ontogenetic cascade from early imitation to elaborated ToM. This would clearly be consistent also with Gallese and Goldman’s [59] hypothesis that MNs and ToM are linked.

6. Mirror neurons and autism

These ideas lead directly to our hypothesis that some dysfunction in the MN system might be implicated in the generation of the constellation of clinical features which constitute the autistic syndrome. The most basic hypothesis would be that there is a failure or distortion in the development of the mirror neuron system. This could be due to genetic or other endogenous causes, to external conditions adverse to MN functioning, or some interaction between these. Such factors might affect all MN groups or be confined to just certain groups such as those in the parietal cortex. Complete failure is not necessarily implied, for there might be merely a degree of delay or incomplete development.

Considering the factors discussed in previous sections, such dysfunction could prevent or interfere with imitation, or perhaps more fundamentally, lead to the ‘impaired formation/co-ordination of specific self-other representations’ proposed to lie at the root of the cascade of autistic problems [21]. This in turn could explain the failure to develop reciprocal social abilities including shared/joint attention, gestural recognition and language (particularly the social/pragmatic aspects that Rogers and Pennington [21] note are the most affected), as well as breakdowns in the development of empathy and a full ToM.

Such a simple ‘MN-dysfunction, imitation-dysfunction’ model is unlikely to provide the whole story, however, insofar as we also need to explain features of repetitive, inflexible and stereotyped behaviour and language that appears to incorporate some copying from others, in some patients with autism. We would suggest that in fact these latter features are testimony to the perception-action linkage problems that occur in autism; they are consistent with the hypothesis that in autism, the mirror neuron system is as a whole malfunctioning. In these cases the system might be evidencing poor modulation. Recall that it has been suggested that a controlled inhibitory system is essential for allowing MN’s to operate ‘off-line’ for simulation ToM to function and develop. If damage extends to such inhibitory components, then certain forms of mimicry might occur, yet be oddly performed.

7. Autism, executive functions and mirror neurons

In recent years it has been shown that autistic individuals

experience difficulties in executive functions like planning [68–72]. It tends to be assumed that executive functions such as planning ability and attentional shifting are the product of developmental processes largely restricted to the individual. But it is also possible that the child learns something of these functions from others, perhaps initially in relatively concrete contexts, such as playing with building bricks in infancy, and then at higher levels of abstraction and over longer time frames, such as planning meals. The initial stages in such a process might correspond to some kind of ‘program-level’ imitation [73]. There is evidence for this in three-year-old children who are able to acquire, by imitation, alternative hierarchical plans for running off a sequence of actions to complete a functional task [74]. Insofar as MNs code for actions on objects, directed towards a goal, they could be key elements in such a process [75], helping to translate perceived executive functions into praxis and then generalising them to similar situations. With poor MN development, the key building blocks permitting planning functions to be acquired from the external culture might be unavailable.

If mirror neurons play a part in the development of executive function as well as ToM, one would expect to see a correlation between performance on tests of each of the two abilities. This has recently been demonstrated [76]. The same principles may apply to the acquisition of other executive functions, such as approaches to problem solving and attentional shifting, which can be a problem for autistic children [68,69]. Evidence in favour of this proposition comes from Griffiths et al. [77]. They found that apart from tests requiring rule reversal, there was no deficit of executive function in children under 4 years of age with autism. This suggests that the executive deficits are not primary but arise later on in a disrupted pattern of development. Some executive functions, including inhibition and possibly visual working memory appear to be spared in autism [4,67,78,79]. These might be functions much less easily learnt by imitation.

Autistic children show not only characteristic ToM and planning deficits, but also impairment in reconstructing the personal past [80]. Suddendorf [81–83] has proposed that the executive capacity to disengage or dissociate from one’s actual current state (putting it offline, as it were) in order to simulate alternative states underlies both ‘theory of mind’ and mental ‘time-travel’—the ability to mentally construct possible (e.g. planned) events in the future and reconstruct personal events from the past. Thus, in this account mirror neurons may be implied through simulation and executive functions.

8. Neuroimaging mirror neurons and ‘theory of mind’

If ToM and related social deficits in autism are the result of a poorly functioning system of mirror neurons, this might be manifest in recent neuroimaging studies

with relevant tasks. The mirror neuron region has been implicated in reading facial emotion in a normal population [84]. Similarly, a task that involved reading emotional expressions from looking at images of eyes, found that individuals with autism showed less involvement of areas normally activated during emotional interpretation, namely the left putative mirror-neuron region (BA 44/45), the superior temporal gyrus (BA 22) bilaterally, the right insula and the left amygdala [85]. A recent review [86] of studies of both typical individuals and those with autism, seeking to identify sites active in ToM functions found that a well demarcated area of the paracingulate gyrus has been consistently implicated, as have areas of the anterior cingulate cortex but not the mirror neuron regions. The paracingulate gyrus and the anterior cingulate cortex are closely linked and receive dense serotonergic innervation, consistent with them performing a modulatory function and this could explain their involvement. One possible reason for the failure of these tasks to activate MN regions may be related to the control tasks that have been used. As these have been predominantly action-based such as following an action-based story, they would be expected to activate the MN regions as much as the ToM task, so discounting their apparent relevance.

9. Testing the hypothesis

From our hypothesis, several testable predictions flow. First, imitative deficits should be apparent in autism especially where studies take place in the earliest years such as in the study by Charman et al. [87]. Particular aspects of imitation expected to be most susceptible are those where imitation involves a co-ordinated activity between different modes of sensory input, different groups of action-coding neurons and self-other visual transformations.

Secondly, we suggest that the McGurk effect [88] whereby the perceived sound is altered by perceiving lip movements making a different sound, may be the result of MN functioning. In this case we predict that on testing groups of children with autism, non-standard McGurk effects will be apparent.

A third prediction can be related to the work of Baron-Cohen et al. [64] using the CHAT screening test for autism. These authors found that joint attention at 18 months was a predictive screening item for autism (focussing on siblings of individuals with autism). Our hypothesis predicts that even earlier, appropriately-sensitive screening for an imitative deficit would be predictive in this way.

Fourth, we would predict that imaging studies will indicate altered activation of putative MN regions in the brain during imitation tasks attempted by subjects with autism. Similarly, electrophysiologic studies will show altered muscle activity during the observation of actions, whether facial, vocal or with the hands.

One recent study has attempted to examine mirror neurone activity in Asperger's syndrome [89]. Magnetoencephalography was used to detect a decrease in the 20 Hz activity that occurred in the MN region during median nerve stimulation whilst subjects viewed an action. The study did not find a significant difference between the five Aspergers' participants and a control group. Our analysis predicts that more extensive testing of people with autism will reveal such a difference. With the small sample size and small expected effect size (the hypothesis was tested in older individuals with the milder form of the disorder) this first study had minimal power and there was a high risk of a type two error. It is therefore important that further work is extended to larger groups with other characteristics.

10. Conclusion

The discovery of mirror neurons offers a potential neural mechanism for the imitation of actions as well as other aspects of understanding social others. Evolution of this system may have been critical in the emergence of proto-culture and Machiavellian manoeuvring in the most encephalized non-human primates, followed by elaborate ToM and language in humans [90]. In the development of the human child, mirror neurons may be key elements facilitating the early imitation of actions, the development of language, executive function and the many components of ToM. A failure to develop an intact, sensitively regulated, mirror neuron system may therefore impair the development of these important human capabilities.

Our exploration of this hypothesis highlights numerous aspects of our ignorance. Unanswered questions include:

1. What other cognitive and neural capacities work in conjunction with MNs to support imitation and ToM functions?
2. How do MNs relate to other social information processing neurons in performing social cognitive functions?
3. How physically extensive are MN functions which relate to autism? Do they just exist in Broca's area or are there such groups in locations such as parietal cortex, paracinate gyrus and superior temporal sulcus?
4. Do MNs have functions in non-visual modalities as preliminary reports suggest (C. Keysers, E. Kohler, A. Umiltà, V. Gallese and G. Rizzolatti, personal communication; Baker and Perrett, unpublished studies)? For example, is the sound of an action (or vocal utterance) mirrored by the same neurons as those which mirror its sight? What is the range of actions addressed by MNs?

Despite the various candidates suggested in the literature, a 'prime mover' source of the complex cascade of impairments that characterise autism has so far proved elusive. We are suggesting that developmental delay or distortion of a mirroring system with an early age of onset could be such a

'prime mover'. The heterogeneity of the autistic condition may argue against a single cause, yet the commonalities of the clinical syndrome nevertheless permit the possibility of a core dysfunctional mechanism. If this mechanism is normally a precursor to a cascade of effects on other variable systems, then its dysfunction is likely to result in a quite variable clinical picture. Our proposal offers such a mechanism, together with some preliminary evidence for its existence and empirically testable hypotheses. If it gains further empirical support, this may suggest important new avenues for both psychological and pharmacological remedial strategies.

References

- [1] Fombonne E. The epidemiology of autism: a review. *Psychol Medicine* 1999;29:769–86.
- [2] Bailey A, Phillips W, Rutter M. Autism: towards an integration of clinical, genetic, neuropsychological and neurobiological perspectives. *J Child Psychol Psychiatry* 1996;37:89–126.
- [3] Cohen DJ, Volkmar F. *Handbook of autism and pervasive developmental disorders*. 2nd ed. New York: John Wiley & Sons, 1997.
- [4] Russell J. *Autism as an executive disorder*. Oxford: Oxford University Press, 1997.
- [5] Baron-Cohen S, Tager-Flusberg H, Cohen DJ, editors. *Understanding other minds—Perspectives from developmental cognitive neuroscience*. 2nd ed. Oxford: Oxford University Press, 2000.
- [6] Kanner L. Autistic disturbances of affective contact. *Nerv Child* 1943;2:217–50.
- [7] Rutter M, Bartak L. Causes of infantile autism: Some considerations from recent research. *J Autism Child Schizopr* 1971;1:20–33.
- [8] American Psychiatric Association. *Diagnostical and statistical manual of mental disorders*. Washington DC: APA, 1994.
- [9] Folstein SE, Santangelo SL, Gilman SE, Piven J, Landa R, Lainhart J, Hein J, Wzorek M. Predictors of cognitive test patterns in autism families. *J Child Psychol Psychiatry* 1999;40:1117–28.
- [10] Sonuga-Barke EJ. Categorical models of childhood disorder: a conceptual and empirical analysis. *J Child Psychol Psychiatry* 1998;39:115–33.
- [11] Happe F. *Autism*. London: UCL Press, 1994.
- [12] Prior M, Eisenmajer R, Leekham S, Wing L, Gould J, Ong B, Dowe D. Are there subgroups within the autistic spectrum? A cluster analysis of a group of children with autistic spectrum disorders. *J Child Psychol Psychiatry* 1998;39:893–902.
- [13] Baron-Cohen S, Leslie AM, Frith U. Does the autistic child have a 'theory of mind'. *Cognition* 1985;21:37–46902.
- [14] Happe F, Frith U. The neuropsychology of autism. *Brain* 1996;119:1377–400.
- [15] Leslie AM. The theory of mind impairment in autism: evidence for a modular mechanism of development? In: Whiten A, editor. *Natural theories of mind: Evolution, development and simulation of everyday mindreading*. Oxford: Basil Blackwell, 1991. p. 63–78.
- [16] Baron-Cohen S. Theory of mind and autism: a fifteen year review. In: Baron-Cohen S, Tager-Flusberg H, Cohen DJ, editors. *Understanding other minds—Perspectives from developmental cognitive neuroscience*, 2nd ed. Oxford: Oxford University Press, 2000. p. 3–20.
- [17] Leslie AM. Pretense and representation in infancy: the origins of 'theory of mind'. *Psychol Rev* 1987;94:84–106.
- [18] Baron-Cohen S. Precursors to a theory of mind: understanding attention in others. In: Whiten A, editor. *Natural theories of mind*. Oxford: Basil Blackwell, 1991. p. 233–51.
- [19] Boucher J. What could possibly explain autism? In: Carruthers P,

- Smith PK, editors. Theories of theories of mind, Cambridge: Cambridge University Press, 1996. p. 223–41.
- [20] Hobson RP. Autism and the development of mind. UK: Lawrence Erlbaum Associates Ltd, 1993.
- [21] Rogers SJ, Pennington BF. A theoretical approach to the deficits in infantile autism. *Dev Psychopathol* 1991;3:137–62.
- [22] Whiten A. Imitation, pretence and mindreading: secondary representation in comparative primatology and developmental psychology. In: Russon AE, Bard KA, Parker ST, editors. Reaching into thought: The minds of the great apes, Cambridge: Cambridge University Press, 1996. p. 300–24.
- [23] Whiten A. The Machiavellian mindreader. In: Whiten A, Byrne RW, editors. Machiavellian intelligence II: Evaluations and extensions, Cambridge University Press, 1997.
- [24] Carruthers P, Smith PK. Introduction. In: Carruthers P, Smith PK, editors. Theories of theories of mind, Cambridge: Cambridge University Press, 1996. p. 1–8.
- [25] Perner J. Simulation as explicitation of prediction-implicit knowledge about the mind: arguments for a simulation-theory mix. In: Carruthers P, Smith PK, editors. Theories of theories of mind, Cambridge: Cambridge University Press, 1996. p. 90–104.
- [26] Meltzoff A, Gopnik A. The role of imitation in understanding persons and developing a theory of mind. In: Baron-Cohen S, Tager-Flusberg H, Cohen DJ, editors. Understanding other minds, perspectives from autism, Oxford: Oxford University Press, 1993.
- [27] Smith IM, Bryson SE. Imitation and action in autism: a critical review. *Psychol Bull* 1994;116:259–73.
- [28] Rogers S. An examination of the imitation deficit in autism. In: Nadel J, Butterworth G, editors. Imitation in infancy, Cambridge: Cambridge University Press, 1999. p. 255–83.
- [29] Whiten A, Brown J. Imitation and the reading of other minds: perspectives from the study of autism, normal children and non-human primates. In: Braten S, editor. Intersubjective communication and emotion in ontogeny: A sourcebook, Cambridge University Press: Cambridge, 1999. p. 260–80.
- [30] Rogers SJ, Bennetto L, McEvoy R, Pennington BF. Imitation and pantomime in high-functioning adolescents with autistic spectrum disorders. *Child Dev* 1996;67:2060–73.
- [31] Hobson RP. Lee A. Imitation and identification in autism. *Journal of Child Psychology and Psychiatry* 1999;40:649–60.
- [32] DeMeyer MK, Alpern GD, Barton S, DeMyer WE, Churchill DW, Hingtgen JN, Bryson CQ, Pontius W, Kimberlin C. Imitation in autistic, early schizophrenic and non-psychotic subnormal children. *J Autism Child Schiz* 1972;2:264–87.
- [33] Merians AS, Clark M, Poizner H, Macauley B, Gonzalez-Rothi LJ, Heilman K. Visual-imitative dissociation apraxia. *Neuropsychologia* 1997;35:1483–90.
- [34] Goldenberg G, Hagman S. The meaning of meaningless gestures: A study of visuo-imitative apraxia. *Neuropsychologia* 1997;5:333–41.
- [35] Goldenberg G. Imitating gestures and manipulating a mannikin - the representation of the human body in ideomotor apraxia. *Neuropsychologia* 1995;33:63–72.
- [36] Meltzoff A, Moore MK. Persons and representation: why infant imitation is important for theories of human development. In: Nadel J, Butterworth G, editors. Imitation in infancy, Cambridge University Press, 1999. p. 9–35.
- [37] Perrett DI, Smith PAJ, Potter DD, Mistlin AJ, Head AS, Milner AD, Jeeves MA. Neurons responsive to faces in the temporal cortex: Studies of functional organization, sensitivity to identity and relation to perception. *Human Neurobiol* 1984;3:197–208.
- [38] Perrett DI, Smith PAJ, Mistlin AJ, Chitty AJ, Head AS, Potter DD, Broennimann R, Milner AD, Jeeves MA. Visual analysis of body movements by neurons in the temporal cortex of the macaque monkey: a preliminary report. *Behav Brain Res* 1985;16:153–70.
- [39] Perrett DI, Harries MH, Benson PJ, Chitty AJ, Mistlin AJ. Retrieval of structure from rigid and biological motion; an analysis of the visual response of neurons in the macaque temporal cortex. In: Troscianko T, Blake A, editors. AI and the eye, Chichester: J. Wiley & Sons, 1990. p. 181–201.
- [40] Oram MW, Perrett DI. Responses of anterior superior temporal polysensory (STP) neurons to 'biological motion' stimuli. *J Cog Neurosci* 1994;6:99–116.
- [41] Perrett DI, Harries MH, Bevan R, Thomas S, Benson PJ, Mistlin AJ, Chitty AJ, Hietanen J, Ortega JE. Frameworks of analysis for the neural representation of animate objects and actions. *J Exp Biol* 1989;146:87–114.
- [42] Perrett DI, Emery NJ. Understanding the intentions of others from visual signals: neurophysiological evidence. *Curr Psychol Cog* 1994;13:683–94.
- [43] Emery NJ, Perrett DI. How can studies of the monkey brain help us understand 'theory of mind' and autism in humans. In: Baron-Cohen S, Tager-Flusberg H, Cohen DJ, editors. Understanding other minds—perspectives from developmental cognitive neuroscience, 2nd ed. Oxford: Oxford University Press, 2000.
- [44] Jellema T, Oram MW, Baker CI, Perrett DI. Cell populations in the banks of the superior temporal sulcus of the macaque and imitation. In: Meltzoff A, Prinz W, editors. The imitative mind: development, evolution, and brain bases, 2001 (in press).
- [45] Jellema T, Baker CI, Wicker B, Perrett DI. Neural representation for the perception of the intentionality of hand actions. *Brain Cog* 2001;44:280–302.
- [46] Gallese V, Fadiga L, Fogassi L, Rizzolatti G. Action recognition in the premotor cortex. *Brain* 1996;119:593–609.
- [47] Rizzolatti G, Fadiga L, Matelli M, Bettinardi V, Paulesu E, Perani D, Fazio F. Localisation of grasp representations in humans by PET—1: observation vs execution. *Exp Brain Res* 1996;111:246–52.
- [48] Carey DP. 'Monkey see, monkey do' cells. *Current Biol* 1996;6:1087–8.
- [49] Rizzolatti G, Arbib MA. Language within our grasp. *Trends Neurosci* 1998;21:188–94.
- [50] Stevens JA, Fonlupt P, Shiffrar M, Decety J. New aspects of motion perception: selective neural encoding of apparent human movements. *Neuroreport* 2000;11:109–15.
- [51] Hari R, Forss N, Avikainen S, Kirveskari E, Salenius S, Rizzolatti G. Activation of human primary motor cortex during action observation: a neuromagnetic study. *Proc Natl Acad Sci* 1998;95:15061–5.
- [52] Fadiga L, Fogassi G, Pavesi G, Rizzolatti G. Motor Facilitation during action observation: a magnetic stimulation study. *J Neurophysiol* 1995;73:2608–11.
- [53] Grafton ST, Arbib MA, Fadiga L, Rizzolatti G. Localization of grasp representations in humans by positron emission tomography—2: observation compared with imagination. *Exp Brain Res* 1996;112:103–11.
- [54] Rizzolatti G, Fadiga L, Gallese V, Fogassi L. Premotor cortex and the recognition of motor actions. *Cog Brain Res* 1996;3:131–41.
- [55] Iacoboni M, Woods RP, Brass M, Bekkering H, Mazziotta JC, Rizzolatti G. Cortical mechanisms of human imitation. *Science* 1999;286:2526–8.
- [56] Fogassi L, Gallese V, Fadiga L, Rizzolatti G. Neurons responding to the sight of goal-directed hand/arm actions in the parietal area PF (7b) of the macaque monkey. *Soc Neurosci Abstracts* 1998;25(5):654.
- [57] Liberman AM, Cooper F, Shankweiler M, Studdert-Kennedy M. Perception of the speech code. *Psychol Rev* 1967;74:431–61.
- [58] Liberman AM, Whalen DH. On the relation of speech to language. *Trends in Cognitive Sciences* 2000;4:187–96.
- [59] Gallese V, Goldman A. Mirror neurons and the simulation theory of mind-reading. *Trends Cog Sci* 1998;2:493–501.
- [60] Gallese V. Agency and motor representations: new perspectives on intersubjectivity. ISC working papers 2000-6. Workshop on Autism and the Theory of Mind, Lyon, 18th May, 2000. <http://www.isc.cnrs.fr/wp/wp00-6.htm>.
- [61] Hatfield E, Caciopoo JT, Rapson RL. Emotional contagion. New York: Cambridge University Press, 1994.

- [62] Surakka V, Hietanen JK. Facial and emotional reactions to Duchenne and non-Duchenne smiles. *Int J Psychophysiol* 1998;29:23–33.
- [63] Baron-Cohen S. *Mindblindness: An essay on autism and theory of mind*. Cambridge, MA: Bradford Books, MIT Press, 1995.
- [64] Baron-Cohen S, Cox A, Baird G, Swettenham J, Nightingale N, Morgan K, Drew A, Charman T. Psychological markers in the detection of autism in infancy in a large population. *Brit J Psychiat* 1996;168:158–63.
- [65] Visalberghi E, Frigaszy D. Do monkeys ape? In: Parker S, Gibson K, editors. *Language and intelligence in monkeys and apes: Comparative developmental perspectives*, Cambridge, UK: Cambridge University Press, 1990. p. 247–73.
- [66] Whiten A, Ham R. On the nature and evolution of imitation in the animal kingdom: Reappraisal of a century of research. *Advance Study Behav* 1992;21:239–83.
- [67] Whiten A. Primate culture and social learning. *Cog Sci* 2000;24:477–508.
- [68] Hughes C, Russell J, Robbins TW. Evidence for executive dysfunction in autism. *Neuropsychologia* 1994;32:477–92.
- [69] Hughes C. Planning problems in autism at the level of motor control. *J Autism Dev Disord* 1996;26:99–107.
- [70] Ozonoff S, Pennington B, Rogers SJ. Executive function deficits in high-functioning autistic individuals: relationship to theory of mind. *J Child Psychol Psychiatry* 1991;32:1081–105.
- [71] Ozonoff S, Jensen J. Specific executive function profiles in three neurodevelopmental disorders. *J Autism Dev Disord* 1999;29:171–7.
- [72] Pennington BF, Ozonoff S. Executive Functions and Developmental Psychopathology. *J Child Psychol Psychiatry* 1996;37:51–87.
- [73] Byrne RW, Russon AE. Learning by imitation: a hierarchical approach. *Behav Brain Sci* 1998;21:667–721.
- [74] Whiten A. Imitation of sequential and hierarchical structure in action: experimental studies with children and chimpanzees. *Proceedings of the AISB Convention, Symposium on Imitation in Animals and Artefacts*, Edinburgh, 1999. p. 38–46.
- [75] Byrne RW. Imitation without intentionality. Using string parsing to copy the organization of behaviour. *Animal Cognition* 1999;2:63–72.
- [76] Perner J, Lang B. Development of theory of mind and executive control. *Trends Cog Sci* 1999;3:337–44.
- [77] Griffith EM, Pennington B, Wehner EA, Rogers SJ. Executive functions in young children with autism. *Child Development* 1999;70(4):817–32.
- [78] Ozonoff S, Strayer DL. Inhibitory function in non-retarded children with autism. *J Autism Dev Disord* 1997;27(1):59–77.
- [79] Hughes C, Leboyer M, Bouvard M. Executive function in parents of children with autism. *Psychological Medicine* 1997;27:209–20.
- [80] Klein SB, Chan RL, Loftus J. Independence of episodic and semantic self-knowledge: the case from autism. *Soc Cog* 1999;17:413–36.
- [81] Suddendorf, T. *Discovery of the fourth dimension: mental time travel and human evolution*. Master's thesis, University of Waikato, Hamilton, New Zealand, 1994. Internet: <http://cogprints.soton.ac.uk>.
- [82] Suddendorf T, Corballis MC. Mental time travel and the evolution of the human mind. *Genetic, Social, and General Psychology Monographs* 1997;123:133–67.
- [83] Suddendorf T. The rise of the metamind. In: Corballis MC, Lea CS, editors. *The descent of mind*, Oxford: Oxford University Press, 1999. p. 218–60.
- [84] Nakamura K, Kawashima R, Ito K, Sugiura M, Kato T, Nakamura A, Hatano K, Nagumo S, Kubota K, Fukuda H, Kijima S. Activation of the right inferior frontal cortex during assessment of facial emotion. *J Neurophysiol* 1999;82:1610–4.
- [85] Baron-Cohen S, Ring HA, Wheelwright S, Bullmore ET, Brammer MJ, Simmons A, Williams CR. Social intelligence in the normal and autistic brain: an fMRI study. *Eur J Neurosci* 1999;11:1891–8.
- [86] Frith U, Frith C. The physiological basis of theory of mind: functional neuroimaging studies. In: Baron-Cohen S, Tager-Flusberg H, Cohen DJ, editors. *Understanding other minds—Perspectives from developmental cognitive neuroscience*, 2nd ed. Oxford: Oxford University Press, 2000.
- [87] Charman T, Baron-Cohen S. Another Look at Imitation in Autism. *Dev Psychopathol* 1994;6:403–13.
- [88] McGurk H, MacDonald JW. Hearing lips and seeing voices. *Nature* 1976;264:746–8.
- [89] Avikainen S, Kulomaki T, Hari R. Normal movement reading in Asperger subjects. *Neuroreport* 1999;10:3467–70.
- [90] Whiten A, Byrne RW. *Machiavellian intelligence II: Evaluations and extensions*. Cambridge University Press, 1997.