speech does: as the action unfolds, the same motor commands are activated in the observer as in the agent (e.g. M. Gangitano, Mottaghy and Pascual-Leone 2001; Fadiga, Craighero, *et al.* 2002). In the case of speech, there is wide agreement about at least one purpose of mirroring motor cognition, for it enables one to identify phonemes or allophones reliably in the face of variation in acoustic and visual signals (Liberman and Mattingly 1985). In this way, mirroring motor cognition plays an essential if modest role in linguistic communication. In the case of action observation, however, there is marked disagreement about the utility of mirroring motor cognition. Claims that mirroring motor cognition provide direct knowledge of others' intentions (e.g. Fogassi, Ferrari, *et al.* 2005) face insurmountable objections (Jacob and Jeannerod 2005; Borg 2007). On the other hand, weakening these claims so that mirroring motor cognition provides knowledge only of sequences of small-scale motor actions and their outcomes (e.g. Gallese, Keysers and Rizzolatti 2004) leaves its utility unclear because it is unclear why knowing the outcomes of small-scale motor actions matters. After all, the outcome of grasping a ball is just having a ball in your hand; action interpretation seems to be concerned with why the ball is there. In fact, recently some researchers have shifted emphasis from action understanding to suggestions that the utility of mirroring may consist in its allowing us to discover facts about objects rather than agents (Rotman, Troje, *et al.* 2006) or to disconfirm prior goal attributions rather than do identify goals (Csibra 2007). On the face of it, then, there is a problem about the function of mirroring motor cognition in action observation.

A natural conjecture connects behaviour reading with mirroring motor cognition. One function of mirroring motor cognition is to segment the flow of behaviour and to represent the fundamental chunks (Rizzolatti, Fogassi and Gallese 2001; Byrne 2003). If this is correct, the role of mirroring motor cognition in understanding action is comparable to its role in understanding speech: it does not give us direct insight into intentional or semantic properties, but it does play a fundamental role in the ascription of those properties by enabling us to identify the units and patterns of behaviour that are vehicles of intention and meaning.

This conjecture about the function of mirroring motor cognition tells us two things about behaviour reading. First, the primitive chunks of behaviour are represented by motor commands. (This explains how it is possible to represent them without insight into the nature of the motor system.) Second, the primitive chunks of behaviour are the motor actions to which the mirroring motor system is sensitive. Accordingly we can lever the existing research on invariance in the responses of mirror neurons (e.g. Umiltà, Kohler, *et al.* 2001) and motor cognition (e.g. Massimo Gangitano, Mottaghy and Pascual-Leone 2004) to make predictions about the nature of the chunks on which behaviour reading builds.

In short, then, speech perception is a case of behaviour reading more generally and mirroring motor cognition plays the same role in all behaviour reading that it plays in speech perception: it enables us to segment and represent the primitive chunks of behaviour which are the building blocks for larger patterns corresponding to intentional actions.

The following sections support the claims made in this outline. Behaviour reading is given a selective but relatively detailed overview because no recent survey of this literature exists.

II. Behaviour reading

Behaviour reading involves segmenting a stream of bodily movement into chunks and discerning structural relations among chunks on the basis of statistical patterns and other cues. To illustrate, chunks may include reaching, tearing, poking, or orienting to an object or location; and patterns may include orienting to an object's raising the probability of reaching for it.

Behaviour reading is held to be useful or even necessary for recognising intentions (Newtson, Engquist and Bois 1977: 861; D. A. Baldwin, Baird, *et al.* 2001: 708). Behaviour reading may also have functions independently of a capacity to ascribe intentions: efficiently representing events (Kurby and Zacks 2008), discerning structure in actions in such a way as to identify their effects (Byrne 1999), and predicting either what others will do (Povinelli 2001) or when an event likely to be of interest will occur (Swallow and Zacks 2008: 121).

Behaviour reading is also thought to be important for development. Much as identifying phonemes, grouping them into word-like clusters and uncovering clause-like clusters in these patterns is held to "bootstrap" the development of linguistic comprehension (Werker and Yeung 2005), so also behaviour reading is held to be a steppingstone to understanding intentional action (Saylor, Baldwin, *et al.* 2007). This is plausible because (as we will see) behaviour reading identifies the structures to which ascriptions of belief, desire and intention are explanatory.

Segmenting chunks. Experimental research on behaviour reading was pioneered by Darren Newtson who showed adults a five minute silent video of a man performing everyday activities in an unbroken sequence, including filling in a questionnaire, putting a match into a bin and stamping out a cigarette on the floor. Subjects were asked to identify the boundaries of fine-grained chunks that were "meaningful sequences of action" (1973). Newtson found reliable intra- and interpersonal agreement on the location of such boundaries, and also that boundaries shift depending on context (see Newtson, Engquist and Bois 1977: 847 for an overview: he calls the boundaries "breakpoints"). These results have been confirmed using indirect behavioural measures (Newtson and Engquist 1976) and fMRI (Zacks, Braver, *et al.* 2001; Zacks, Swallow, *et al.* 2006). Follow-up work has shown that extracting chunks of behaviour occurs automatically and online, so may be a perceptual process (Zacks, Tversky and Iyer 2001). This suggests extracting chunks of behaviour may be compared to the perceptual segmentation of phonemes from acoustic and visual stimuli.

Newtson hypothesised that chunks of behaviour serve as an intermediate representation for ascribing intention. This hypothesis is supported by the discovery that segmenting chunks has effects on narrative comprehension, recognition, learning and memory (see Kurby and Zacks 2008 for a review). Perhaps, then, comparison with speech can be extended: the role of phonemes in linguistic comprehension may provide a useful model for the role of the role of behaviour chunks in attributing beliefs, desires and intentions (D. Baldwin and Baird 2001).

One problem noted above concerns the nature and representation of these behavioural chunks. This problem will be discussed later; for now I take for granted that suitable chunks occur.

The usefulness of behaviour reading depends on the complexity of the patterns that can be discerned. A key distinction is between 'serial' and 'hierarchical' patterns. This distinction is analogous to that between finite state and phrase structure grammars (Chomsky 1956), but can be understood informally for present purposes. Serial patterns involve relations among consecutive chunks of behaviour and so can be identified by relatively simple learning mechanisms that track statistical relations between pairs of consecutive chunks (Conway and Christiansen 2001). Some serial patterns arise from the fact that pursuit of a goal characteristically involves a sequence of adjacent chunks; for example, eating a hamburger involves grasping it and then repeatedly brining it to the mouth. Hierarchical patterns involve relations among non-consecutive chunks. Such patterns sometimes occur because pursuit of a goal involves subgoals that can be performed in different orders, as when making a burger involves preparing the bun and fillings individually before bringing them together. Patterns in the behavioural chunks that constitute burger-making activities cannot be learnt only by tracking relations between pairs of consecutive chunks.

The nature and recognition of these patterns can be understood on the model of speech perception, where the organisation of phonemes into words counts as a sequential pattern (ignoring, for simplicity, complex variability in the allophones that realise phonemes) and organisation of words into clauses counts as an hierarchical pattern.

Sequential patterns. Consider the following sequence of mundane actions:

> … push door, walk through frame, walk to desk, grasp paper, orient to pen, reach for pen, write on paper, fold paper, place pen, reach for headphones, push button, …

Here the flow of movements is described in terms of phoneme-like chunks that infants and adults can readily identify (Saylor, Baldwin, *et al.* 2007). Infants (from around 9 months) and adults can also group these chunks into word-like units such as the letter-writing sequence in the above example: these are chunks that seem to belong together and to be separate from previous and ensuing chunks (Saylor, Baldwin, *et al.* 2007). The boundaries of these units are generally "intention-relevant" (Saylor, Baldwin, *et al.* 2007), corresponding to the completion of a goal or subgoal.

In some cases, identifying these word-like behaviour units involves ascriptions of intention or purpose (Zacks 2004). However, ascribing intention is not generally necessary for isolating these units. There are also at least two types of non-intentional cue to their boundaries. First, commencement and completion of a goal or subgoal typically coincide with dramatic changes in the physical features of the movements (Zacks, Tversky and Iyer 2001). Baldwin and Baird express this idea graphically with the notion of a "ballistic trajectory that provides a temporal contour or 'envelope' demarcating one intentional act from the next" (D. Baldwin and Baird 2001). Research using schematic animations has shown that adults use a variety of movement features to group behavioural chunks into word-like units (Zacks 2004; Bridgette M. Hard, Tversky and Lang 2006). The second non-intentional cue is statistical. Chunks of behaviour that are all steps to a single goal or subgoal are more likely to occur in succession than chunks not so related; thus transitional probabilities in the sequence of chunks could in principle be used to identify intention-relevant units, much as phonemes can be grouped into words by means of tracking transitional probabilities (J. R. Saffran, Newport and Aslin 1996; Gómez and Gerken 2000). In fact, Baldwin and colleagues demonstrated that adults can learn to group small chunks of behaviour into larger word-like units on the basis of statistical features alone (2008). And since the statistical learning mechanism required for discerning such units is automatic (Fiser and Aslin 2001), domain-general (Kirkham, Slemmer and Johnson 2002) and present in other species including monkeys (Hauser, Newport and Aslin 2001) and rats (Toro, Trobal¢ and n 2005), it seems plausible to suppose that sensitivity to intention-relevant units in sequences of behavioural chunks can be found in individuals that lack the ability to ascribe intentions or goals.

In short, relatively humble learning mechanisms enable chunks of behaviour to be grouped into word-like units on the basis of ballistic envelopes and transitional probabilities. Just as words are semantically relevant units yet can be discerned without knowledge of semantics, so these behavioural units have boundaries corresponding to the fulfilment of intentions but can be identified without knowledge of intention.

Note that discerning pattern in sequences of behaviour is not limited to intention-relevant units: behaviour reading may group behavioural chunks into units that have no clear relevance to a goal, as studies requiring subjects to segment behaviours using reversed animations and other manipulations show (Bridgette M. Hard, Tversky and Lang 2006; D. Baldwin, Andersson, *et al.* 2008; Swallow and Zacks 2008). Similarly, use of statistical cues to group phonemes into words does not yield only meaningful words. Discerning intention-**ir**relevant units may be undesirable overgeneration or it may have predictive value. The definition of behaviour-reading allows for the exploitation of any useful patterns, not just those induced by goals and intentions.

Hierarchical patterns. In discussing sequential patterns we were concerned with grouping together strings of consecutive behavioural chunks. But there are also patterns in behaviour connecting non-consecutive chunks. For example, making a burger involves several steps whose order is only loosely constrained, where some of these steps can be omitted or replaced (veggie burger, hamburger) and where steps can be interspersed with irrelevant actions (answering the phone). Grouping together all and only the behavioural units involved in making a burger therefore involves discerning hierarchical structure. Clearly this is possible, but is it possible independently of ascribing intention?

Richard Byrne studied Rwandan mountain gorillas' preparation of nettles for eating, a complex task involving several sub- and sub-sub-goals (2003). He identified two types of cue that reveal structure in this behaviour. The first type of cue depends on comparing different occasions: repetitions, omissions, pauses and substitutions indicate boundaries of significant units, as do points where one-off (and therefore probably extraneous) behaviours are interwoven and the points where recovery from interruption happens smoothly. The second type of cue includes changes in motion features and pauses. I shall call these "prosodic" cues because they resemble cues such as changes in pitch and pauses used by infants to identify clause boundaries (e.g. Soderstrom, Nelson and Jusczyk 2005; Seidl and Cristi… 2008).

The existence of such cues shows that it is possible in principle to identify plan-induced hierarchical patterns in behaviours without knowledge of intention. Is there any evidence on whether these cues are in fact detected?

Several researchers who appear to be addressing this question are actually concerned only with identifying word-like units (Zacks, Tversky and Iyer 2001; Bridgette M. Hard, Tversky and Lang 2006; Bridgette Martin Hard, Lozano and Tversky 2006; Kurby and Zacks 2008). They label this 'hierarchical structure' because flowing motion is first being divided into phoneme-like behavioural chunks whose organisation then defines boundaries of larger word-like units. We can thus regard the chunks as parts of larger units, which justifies the label 'hierarchical'. However, discerning word-like units only requires sequential *learning*—it only requires tracking associations between consecutive chunks. Sensitivity to these "hierarchical structures" does not imply that one can also detect patterns involving optional components or variable ordering, such as those involved in making a burger or preparing a nettle. Following Conway and Christiansen (2001), I therefore reserve the label 'hierarchical' for patterns involving relations among potentially non-consecutive chunks.

To my knowledge the question of learning genuinely hierarchal patterns in behaviour has not been directly addressed. We do know from research in other domains that hierarchical patterns can be learnt by adults (Newport and Aslin 2004) and infants from 12-months or earlier (J. Saffran, Hauser, *et al.* 2008). Learning hierarchical patterns differs from learning sequential patterns in that it requires attention (Cohen, Ivry and Keele 1990) and there appear to be constraints on the types of pattern that can be learnt (Newport and Aslin 2004).

Infants' ability to identify patterns in action may be boosted by 'motionese'. Brand and colleagues (2002) found that "mothers spontaneously modified their infant-directed actions in a number of ways … a higher level of interactiveness, greater repetitiveness and movements that were larger in scale but reduced in complexity." These modifications may assist infants' efforts to detect hierarchical patterns in behaviour, amplifying and inserting prosodic cues to reduce infants' dependence on statistics.

There is uncertainty on whether non-humans are capable of learning hierarchical patterns of any kind. Evidence for an absence of hierarchical learning has been offered for cotton-top tamarins (Fitch and Hauser 2004) and rats (Toro, Trobal¢ and n 2005), and there is no convincing evidence for such learning in nonhumans generally (Corballis 2007). Inability to learn hierarchical patterns would limit the power of behaviour reading to activities that are often uniformly realised (no variation in the steps taken) and performed without interruption.

In short, executing goals with sub-goals tends to create statistical and prosodic cues in the pattern of behaviours. Discerning these cues makes it possible to recover the structure of the behaviour without knowledge of intention. Such patterns can be discerned by humans, including infants, but possibly not by other animals. Learning these patterns is not automatic and requires attention.

III. What are behaviours?

Current research as overviewed in the previous section has yet to squarely face the question, What are behaviours? In answering this question we can focus on the phoneme-like chunks of behaviour, for more complex behavioural units are built from these. This question should be addressed from the point of view of behaviour readers: What do they represent when they represent behaviour?

This question has two related parts. One concerns factors with respect to which behaviour reading is invariant. To illustrate, reaching for a ball may involve quite different motions on different occasions. Do subjects classify different reaches as instances of a single chunk or as instances of unrelated chunks? The other part of the question is about the nature of these behaviours. Are they intentional actions, bodily movements or what? This is partly a philosophical issue: just as philosophers have attempted to say what intentional action is (e.g. Davidson 1963 [1980], 1971 [1980]; Bratman 1984), so there should be a philosophical account of non-intentional behavioural chunks. But this issue is not narrowly philosophical, for it has implications for how behavioural chunks could be represented.

Our guiding hypothesis is that behaviour reading is possible independently of ascribing goals or intentions. This means that behaviour readers cannot represent chunks of behaviours as intentional actions or in any way that presupposes intentions or goals. A natural alternative is to suppose that behaviour readers represent chunks of behaviours as sequences of movements by bodies or body parts.

This alternative is unacceptable, however. The power of behaviour reading depends on extracting patterns, which requires a relatively small number of chunks that recur. Further, extracting patterns that are sometimes relevant to intentions requires some degree of invariance with respect to anatomical and postural differences between individual agents and environmental obstacles to action. The movements involved in achieving even the simplest goal, such as grasping an apple, vary from occasion to occasion and lack any such invariance.

Comparison with speech is useful here. Phonemes are realised by different allophones on different occasions (Davenport and Hannahs 1998: 96ff.), and allophones in turn are realised by various acoustic signals (Repp and Liberman 1987; Nygaard and Pisoni 1995: 72–5). That is, phonemes are separated from acoustic and visual signals by at least two layers of abstraction. Given the requirements of recurrence and intention-relevance on behavioural chunks, they must be similarly distant from movements. Indeed, variation in many of the same factors affect both speech and action: anatomy, posture, manner of execution (e.g. fast vs. slow), and environmental impediments. Context is a further factor: the way a phonetic gesture or behavioural chunk is realised depends on neighbouring chunks (Davenport and Hannahs 1998: 130ff.; Johnson-Frey, McCarty and Keen 2004). Invariance with respect to context and the other factors requires layers of abstraction between movement and behavioural chunks. This is why the basic chunks used in behaviour reading cannot be movements.

So what is the nature of this abstraction, this analogue of a phoneme in behaviour reading, if it is neither goal-directed not movement? So far no research has directly addressed this question.

Existing research does not directly address this question. In the case of speech, researchers have investigated when subjects classify different stimuli as instances of a single phoneme (e.g. Repp and Liberman 1987), giving rise to detailed claims about the nature of the primitive chunks (e.g. Browman and Goldstein 1992). Newtson, whose work set the scene for contemporary research, did not address the parallel question about when different stimuli are treated as the same behavioural chunks. To my knowledge he never even gave an informal description of the fine-grained segments of behaviour his subjects identified. And his research, which used video, involved unvarying sequence of movements. He showed that inter- and intra-subject agreement on where the boundaries of chunks fall (that is, "breakpoints") when subjects are given precisely the same movements. It is consistent with this finding to deny that relevantly similar boundaries would be identified in other movements that differ superficially but are attempts to achieve the same goals. In principle his findings might be explained by subjects' relying on changes in motion features that do not result in categories applicable to different occasions. So not only do we not know what behavioural chunks are, there is no direct evidence that they even exist.

Recent research has generally ignored this lacuna (Loucks and Bladwin 2006: 240). The nature of the stimuli, which are invariably precisely repeated movements delivered by video or computer, tends to object-directed motor actions. It also tells us something about one function of mirroring motor cognition. It might provide us with an ability to identify motor actions (Gallese, Keysers and Rizzolatti 2004), to predict which motor action will be performed next (Jacob and Jeannerod 2005), or to verify ascriptions of intention (Csibra 2007), and it may facilitate interpersonal coordination (Pacherie and Dokic 2006; Knoblich and Sebanz 2006). But at least as important as any of these functions is its foundational role in behaviour reading and, thereby, theory of mind. This is the truth behind the claim that mirror neurons are part of a mechanism for understanding intentional actions.

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