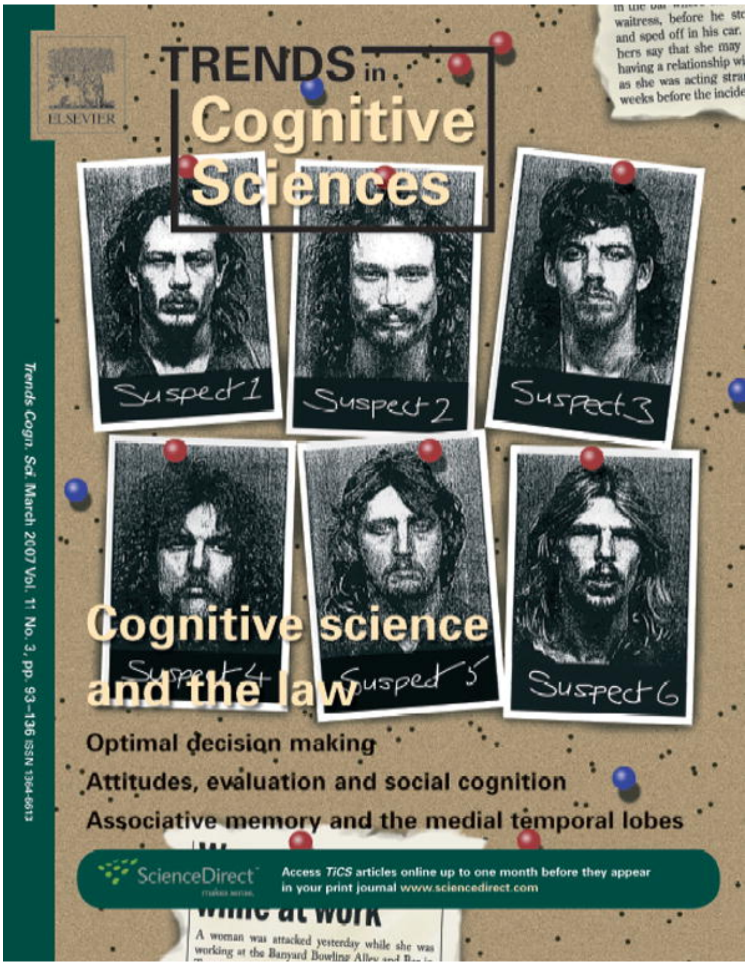
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Do people use language production to make predictions during comprehension?

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We present the case that language comprehension involves making simultaneous predictions at different linguistic levels and that these predictions are generated by the language production system. Recent research suggests that ease of comprehending predictable elements is due to prediction rather than facilitated integration, and that comprehension is accompanied by covert imitation. We argue that comprehenders use prediction and imitation to construct an 'emulator', using the production system, and combine predictions with the input dynamically. Such a process helps to explain the rapidity of comprehension and the robust interpretation of ambiguous or noisy input. This framework is in line with a general trend in cognitive science to incorporate action systems into perceptual systems and has broad implications for understanding the links between language production and comprehension.

Introduction

Traditionally, cognitive scientists have studied perceptual (input) and action (output) processes independently. However, more recently, there has been a move towards their integration [1], with researchers assuming some form of common coding (i.e. shared representations) for perception and action. But this trend has been asymmetric: whereas motor theorists assume that perception contributes to the guidance of action [2], the claim that motor processes contribute to perception has received much less attention. However, Wilson and Knoblich have recently made a strong argument for motor involvement in the specific case of the perception of conspecifics [3].

In the same way, psycholinguists have traditionally studied language comprehension and language production independently, as is apparent in reviews and textbooks [4]. There is some limited interest in the extent to which they share representations (e.g. of words or grammar), but this trend has come from research on language production rather than comprehension. It is uncontroversial that speakers use the comprehension system to monitor their plans and output [5]. In other words, language production uses the comprehension system to assist production. But does the reverse occur – does language comprehension use the production system? And if so, when and why? Whereas production uses comprehension for monitoring, here we argue that comprehension uses production to predict what is coming next.

Psycholinguists have long realized that language comprehension is highly incremental, with readers and listeners continuously extracting the meaning of utterances as they encounter them [6–8], but it has been unclear how this is achieved. As we show here, much recent research suggests that language comprehension can be highly predictive, so long as linguistic or non-linguistic context supports these predictions. Therefore, comprehenders can get ahead of themselves and have more time to keep up with what they are encountering. They can also use prediction to compensate for problems with noisy or ambiguous input. What is the basis for such prediction? A parsimonious explanation is that prediction does not require a special-purpose mechanism but instead uses the same system that is used for production. To see how this might happen, we consider the analogous perceptual case that is provided by Wilson and Knoblich [3].

Facilitating perception through action emulation

Wilson and Knoblich [3] propose that perceiving other people's behaviour activates imitative motor plans, specifically involving what Grush [9] calls 'emulators'. An emulator incorporates a forward model of an external system that runs simulations of that system in real time. Forward models have long been accepted as part of motor-control theory, with people rapidly constructing models of actual movements before making those movements and using those models as guides for corrections. For instance, before moving your arm, you model the path it should take and, if it deviates from that path, you correct accordingly. Such a forward model can be used more rapidly than real-world feedback and, additionally, it provides information about where your arm is likely to be (in the absence of accurate sensory feedback) [2,10].

Wilson and Knoblich argue that emulators can also be used in perception when the behaviour of the target is sufficiently predictable, as occurs when perceiving conspecifics. They point out that covert imitation of action is pervasive, and cite evidence from cognition, social psychology and neuroscience. They go on to claim that covert imitation is not only used to promote overt imitation, to aid the understanding of others' actions after perception

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has taken place, or to support memory for events (i.e. postdictively). Instead, it enhances perception of those actions by predicting what is going to happen next.

The evidence for motor involvement in perceptual prediction comes from studies of representational momentum in human-movement perception. In one study, participants were shown sequences of static body postures that implied continuous motion. They were faster at deciding that particular postures were possible if those postures would have immediately followed the sequence than if they would have immediately preceded the sequence [11]. It seems that viewers constructed a representation of the body-movement sequence that went forward in time, beyond what was shown. Specifically, the perceptual system generated a structured internal model of the target system (the body movements), which was isomorphic on a part-by-part basis to that system. This modelling was possible because the body movements were (essentially) the same as those that the perceiver would make under those circumstances.

If such prediction is motor-based, imitative motor activation ought to occur before or at the time of the target event (rather than after the event, as would be the case if it merely aided understanding of the event). Wilson and Knoblich [3] review evidence in favour of this account. For example, appropriate motor-related brain areas can be activated before a perceived event occurs, and mirror neurons in monkeys can be activated by perceptual predictions as well as by perceived actions. But an early time-course of activation does not prove that imitative motor activation facilitates prediction. Causal evidence comes from the finding that people are better at predicting a movement trajectory (e.g. in dart-throwing or in handwriting) when viewing a video of themselves than when viewing a video of others. Presumably, predicting using one's motor program is most accurate when the object of the prediction is one's own actions.

The use of covert imitation to facilitate perception of other people's behaviour could occur in any domain in which the upcoming behaviour is at least sometimes

Box 1. Prediction in linguistic contexts

Evidence shows that comprehension is facilitated when the upcoming words are highly predictable. For example, people are faster at processing a more predictable word, such as 'the tired mother gave her dirty child a *bath*', than a less predictable one, such as 'the tired mother gave her dirty child a *shower*', even when the words are equally plausible [39]. Likewise, highly predictable words are read quickly and are often skipped during reading [40]. They also lead to reduced N400 event-related potential (ERP) effects (which are indicative of degree of anomaly) [41], as do anomalous words that are semantically related to predicted words [42]. Such observations are consistent with prediction, but they could also occur because predictable words are easier to integrate into the linguistic context. However, this explanation is less compatible with recent evidence. For example, readers and listeners are disrupted when they encounter an adjective (in Dutch) that does not agree in gender with that of an upcoming, highly predictable noun [e.g. 'The secret family safe...was situated behind a *big* (common gender)...', where the predicted *painting* is neuter gender] [43] (Figure I in this box). Comparable results occur with article gender in Spanish [44]. Interestingly, people also seem to anticipate the phonological form of highly predictable nouns, as indexed by whether 'an' rather than 'a' occurs in a context that predicts 'kite'. This prediction seems to be graded (the magnitude of the anomaly effect depends on the degree of predictability) [27]. Finally, a misspelt word that sounds identical to a highly predictable word [e.g. 'boekun' for 'boeken' ('books' in Dutch)] elicits a P600 ERP effect, which seems to reflect a clash between it and the predicted form ('boeken') [45].

Predictions can be made at other linguistic levels. In many cases, predictability is greater at these other levels than at the lexical level (e.g. articles are almost always followed by either nouns or adjectives). People are faster at naming words when they are syntactically compatible with the prior context, even when they bear no semantic relationship to the context [46]. Additionally, there is evidence for prediction of semantic features of words, such as whether they are likely to be concrete or abstract [47]. However, these results could reflect ease of integration rather than prediction. Better evidence comes from Lau *et al.* [28], who found that early syntactic anomaly effects in the ERP record are affected by whether the linguistic context predicts one particular syntactic category for the upcoming word or whether the linguistic context is compatible with different syntactic categories. Specifically, a preposition leads to a stronger early anomaly effect if the context clearly predicts an upcoming noun than if it predicts more than one non-prepositional category [28]. Another study showed that reading 'or the subway' is faster following 'the team took either the train...' than following 'the team took the train' [48]. The presence of 'either' makes the upcoming syntax more predictable by ruling out a misanalysis in which 'or' starts a new clause, and thus facilitates comprehension.

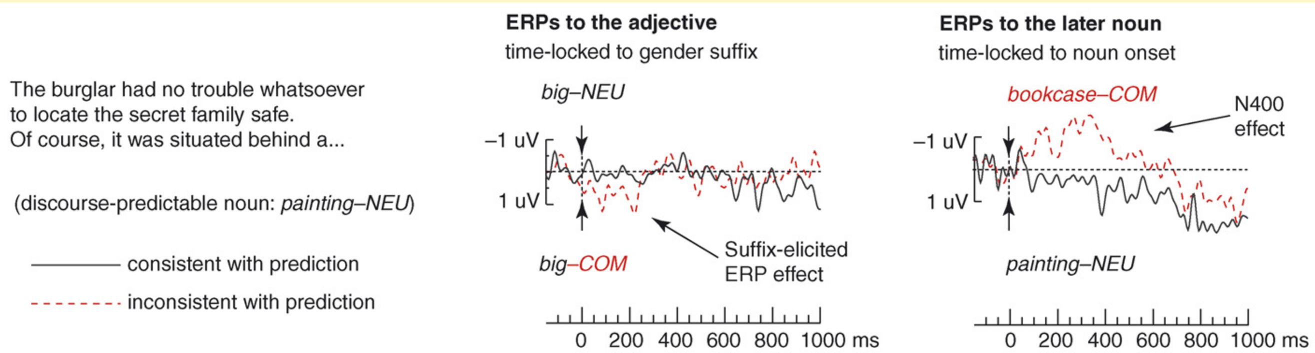

Figure I. Event-related potentials (ERPs) for a single electrode (RT, a right-temporal electrode placed laterally to Cz, at 33% of the interaural distance) while participants listened to Dutch sentences. ERPs for the following sentence are illustrated: 'The burglar had no trouble whatsoever to locate the secret family safe. Of course, it was situated behind a *big (neuter)/big (common) painting (neuter)/bookcase (common)*', where *painting* is predicted and *bookcase* is not predicted. Notice the early development of the positive deflection in the ERP when the participant heard the adjective *big* in common gender (not predicted) as compared with the adjective *big* in neuter gender (predicted). Reproduced, with permission, from Ref. [43]. Abbreviation: uV, microvolts.

predictable and where the perceiver also performs that behaviour him or herself. Both are clearly true for language comprehension. Just as motor involvement during the perception of body movement can facilitate that process of perception, so involvement of the production system during comprehension can facilitate that process of comprehension. Importantly, language involves many levels of representation (e.g. words, sounds, grammar, and meaning), and the production system can be involved at any of these levels. We now summarize evidence for prediction during comprehension and for the activation of the production system during comprehension.

Evidence for linguistic prediction during comprehension

There is clear evidence for prediction during spoken and written language comprehension. First, people seem to predict upcoming words when the linguistic context is sufficiently constraining (so called 'high-Cloze' contexts), as is demonstrated in experiments that use word naming, eye-tracking and event-related potentials. Additionally, contexts can be highly constraining at other linguistic levels. Because an adjective is very likely to be followed by a noun, a comprehender can predict a noun after encountering an adjective. In accord with this, there is evidence for prediction of grammatical categories and aspects of meaning (Box 1).

So far, we have considered prediction in terms of the current linguistic context. However, language is often used to talk about matters at hand and, in such cases, the comprehender can draw on other information, such as the concurrent visual environment. For example, if I point to a wasp and say, 'Look, there's a...', you might be able to predict that I would be about to say 'wasp'. In such cases, there is evidence for prediction of meanings that is measured by the comprehenders' eye movements to potential objects or events (Box 2). A similarly constraining linguistic context is often present in dialogue – for example, when a question seems to require one of a small range of answers (e.g. 'Are you going to behave better in future?').

Activation of the production system in comprehension

Why do we think that these predictions use the production system rather than a system that is internal to comprehension? There is direct evidence of an involvement of articulation in speech comprehension. Listeners activate the appropriate muscles in the tongue and lips while listening to speech but not during non-speech [12,13]. Additionally, increased muscle activity in the lips is associated with increased activity (i.e. blood flow) in Broca's area, which suggests that this area mediates between the comprehension and production systems during speech perception [14]. Thus, comprehension activates the production system and leads to covert imitation. (The motor activation is likely to follow from the activation of the production system rather than itself being the cause of imitation.) There is also evidence for the activation of brain areas that are associated with production during aspects of comprehension from phonology [15] to narrative structure [16]. Evidence of this kind is considered in detail in a recent review of the motor theory of speech perception [17].

Box 2. Prediction in non-linguistic contexts

Several studies have tracked eye movements of participants who listened to sentences while viewing arrays of objects or depictions of events. Participants tended to start looking at edible objects more than at inedible objects when hearing 'the man ate the' (but did not do so when 'ate' was replaced with 'moved') [49]. These predictive eye movements depend on the meaning of the whole context, not just the meaning (or lexical associates) of the verb [50]. Visual information is integrated with prosody [51], grammatical case-marking [52], and discourse context [53] to drive predictive eye movements. In another study, participants listened to 'the princess washes apparently the pirate' (in German) while viewing a picture of a princess washing a pirate and a fencer painting the princess (Figure I in this box). Participants tended to look at the pirate before hearing 'pirate', thereby indicating that they predicted the event (i.e. the princess washing the pirate) [54].

Figure I. Example of the pictures used in Ref. [54] (a princess washing a pirate and a fencer painting a princess). On hearing 'the princess washes apparently...' (in German), participants tended to look at the pirate. Reproduced, with permission, from Ref. [54].

Additionally, during conversation, listeners predict precisely when the current speaker's turn will end and when they should begin speaking. Models of inter-turn intervals suggest that speakers and listeners synchronize their syllabic speech rates during dialogue for this purpose [18]. This process involves entrainment of the speech production system by the comprehension system.

Another reason to suspect that comprehension uses the production system comes from evidence of the pervasiveness of spontaneous (overt) imitation at many linguistic levels, which implies that people construct imitative plans at the relevant stages in the production process [19]. This is most obvious in dialogue, which is highly repetitive. Interlocutors tend to repeat words [20], grammar [21] and different aspects of meaning [20]. Similarly, they imitate accent and speech rate [22], and they adopt increasingly similar phonetic realizations of repeated words [23]. For example, a confederate and a participant took turns to describe pictures to each other (and to find the appropriate picture in an array) [21]. The confederate would describe a picture as 'the cowboy offering the banana to the robber' or 'the cowboy offering the robber the banana' (sentences that have roughly the same meaning but different grammatical forms). Participants showed a strong tendency to repeat grammatical form in their next description. Moreover, comparable effects occur in four- and five-year-old children [24].

For imitation to be used by the comprehension system, it must occur very quickly and without requiring complex decisions or application of potentially scarce resources. This suggests that it needs to be automatic, and there is evidence that it is (e.g. interlocutors are almost entirely unaware that they imitate each other's grammar) [19]. Furthermore, phonological or acoustic imitation is rapid [25], and the faster the imitation, the more faithful it is [26].

A production-based emulator

We now propose that the production system acts as an emulator during language comprehension (Figure 1) [3,9]. At each step, the emulator predicts the next input unit in the speech stream simultaneously at different linguistic levels, such as phonology, syntax and semantics. Whereas it is possible that the emulator simply makes one prediction at each level, we assume that it specifies a range of options that have associated probabilities (because this enables it to benefit, whichever option occurs; this is also compatible with both motor-control theory [10] and experimental evidence [27]). These predictions depend on how constraining the context is at a given linguistic level, just as in other forms of emulation. The emulator is controlled by a Kalman filter, which weights the prediction against the current input and feeds back the result to influence the next prediction of the emulator. Notice that the account deals with the analysis of noisy input as well as with predictive processing.

Assessing this account

Such an emulator that is modulated by input is extremely well suited to the rapid incremental processing of language (and the ability to shadow the input, in particular) [6]. It helps explain why people can detect implausibility so rapidly, sometimes in the first fixation on a word (around 250 ms) [7], and why such anomaly effects should be greater in highly predictive contexts [27,28]. Similarly, the emulator can build up predictions based on the entire prior context, so it does not seem to matter greatly whether implausibility depends on two adjacent words or whether it relates to the incompatibility between a new word and an entire discourse context [8], or even whether it depends on language-internal or real-world implausibility [29].

The emulator framework also helps account for certain linguistic illusions. For example, in the well-known phoneme-restoration effect, listeners misperceive a burst of noise in the speech stream as the occluded phonetic segment (e.g. listeners report hearing the phoneme /æ/ when presented with 'June stroked her pet c[noise]t') [30]. In this example, the uncertainty in the input leads to a greater reliance on the emulation. In addition, readers often fail to

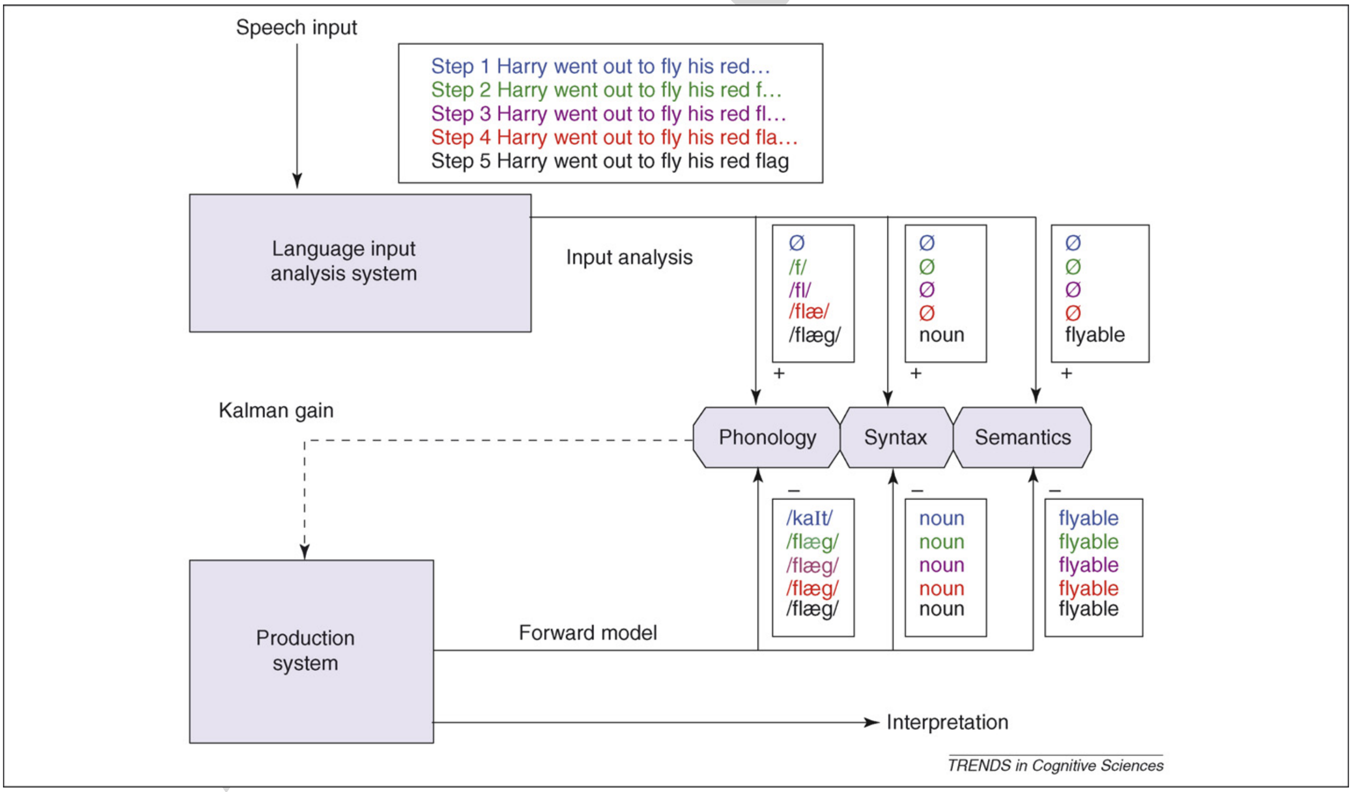

Figure 1. Schematic representation of a production-based language emulator. The emulator is controlled by feedback from a Kalman filter, which weights predictions against analysis of the input at each step. If the prediction is strong and the input noisy, there is low Kalman gain (strong top-down influence on interpretation); if the prediction is poor and the input clear, there is high Kalman gain (strong bottom-up influence). Illustrated are the five steps in comprehending the end of the sentence 'Harry went out to fly his red flag.' At each step, the input analysis and the forward prediction are shown in the same colour for three different levels of prediction (phonology, syntax and semantics). In this case, we make three simplifications. First, the input is noise-free, so that (for instance), at Step 2, the input analysis system is certain that it has encountered /f/ rather than /p/ or /k/. In a noisy environment, it might ascribe a probability of 0.9 to /f/ and 0.1 to other possibilities. Second, we illustrate only a single prediction at each linguistic level, although we assume that a range of predictions are made. In reality, at Step 1, the emulator might ascribe a probability of 0.8 to /kaɪt/ (kite), 0.075 to /flæg/ (flag), 0.1 to /pleɪn/ (plane) and 0.001 to each of various other possibilities; at Step 2, the probability of /flæg/ might go up to 0.95, and so on. By contrast, the probability of the sentence ending in a noun is (virtually) 1 at Steps 1–5. Third, we ignore the possible complexity of the semantic representations (e.g. how fine-grained they are).

recognize anomalies in semantically complex sentences – for example, in the hospital notice 'No head injury is too trivial to be ignored' [31]. Presumably, the emulator overrides the input system at the semantic level to yield an interpretation along the lines of 'No head injury is too trivial to be noticed.'

Finally, the close coupling between production and comprehension that is assumed in the emulator framework is consistent with the claim that imitation in dialogue facilitates the alignment of interlocutors' mental states, which seems to be a hallmark of successful communication [19]. In particular, such imitation facilitates prediction in dialogue: if B overtly imitates A, then A's comprehension of B's utterance is facilitated by A's memory for A's previous utterance. Hence, prediction and imitation can jointly explain why conversation tends to be so easy, even though it involves constant task-switching and the need to determine when to speak and what to say.

However, postdictive and epiphenomenal explanations of why production mechanisms seem to be activated during comprehension cannot be entirely dismissed, any more than it is possible to dismiss analogous explanations in the perception of conspecifics. Thus, Garrett [32] considers a range of evidence for the involvement of production mechanisms in comprehension, but uses it to argue that they provide '...a continual error control mechanism via the production monitoring of partial products of the recognition system' (p. 48), which helps decide among alternative analyses of utterances. Therefore, this is a postdictive account, in which production mechanisms facilitate understanding by resolving ambiguity. However, his evidence is equally compatible with our predictive proposal.

Garrett responds to the concern that intact comprehension seems compatible with impaired production by pointing out that detailed analyses of comprehension in Broca's aphasic patients indicate that it is far from normal. Perhaps more importantly, production and comprehension differ during acquisition, with children comprehending much that they cannot produce. However, this does not mean that children do not engage production processes during comprehension, but merely that they can have difficulty constructing all stages from intention to articulation. Additionally, much comprehension can be 'shallow', with children working out what is meant on the basis of surface cues (e.g. which word comes first). More interestingly, production data suggest that young children do not generalize abstract constructions to novel verbs [33], whereas comprehension data from preferential-looking tasks suggest that they use abstract constructions to interpret utterances [34]. However, Chang *et al.* show that it is possible to reconcile these data in an account in which syntactic abstractions that support production arise from learners' predictions about upcoming words during comprehension [35]. Thus, prediction might have a central role in learning as well as in comprehension.

Our account suggests that production has a causal role in the comprehension of noisy input as well as in prediction. Indeed, production mechanisms should contribute increasingly to comprehension as the quality of the input is reduced (e.g. if the speech is noisy or degraded). There is evidence that left lateral prefrontal cortical regions that are associated with linking production to perception of speech [36] become increasingly active with increasing degradation of speech quality. This has been shown using fMRI (with various forms of speech degradation) [37] and PET (with speech in varying degrees of background noise) [38].

Similarly, our account implies that regions that are associated with production should become increasingly active in increasingly predictable contexts. In addition, activation of tongue and lip muscles should be greater in more predictable contexts, in particular when the prediction can be made at a linguistic level that is close to articulation (e.g. phonology). Other issues for future research are raised in Box 3.

Box 3. Questions for further research

- Does the emulator predict multiple candidates or does it predict only the most likely candidate? Are such predictions in line with theories of language production, which sometimes distinguish the number of candidate words that are postulated at different linguistic levels [55]?
- Is the emulator egocentric or does it include a model of the speaker? If the comprehender would typically produce one word in a particular context (e.g. 'Let's stop for supper') but knows that the speaker would typically produce a different word (e.g. 'dinner'), what does the comprehender predict?
- Do deficits in language production specifically affect on-line comprehension of predictable input?
- Is there a division of labour between input analysis and forward modelling in the emulator, with each being specialized for different kinds or levels of analysis and prediction?

Concluding remarks

In summary, we propose that the production system can be used to facilitate language comprehension, just as the motor system can be used during perception. On the one hand, comprehenders predict upcoming words, grammatical categories and meanings, and the data are straightforwardly explained through the involvement of the production system. On the other hand, people imitate what they have just heard at various linguistic levels. We have argued that they also covertly imitate and that such imitation enables the production system to make predictions, which in turn facilitate comprehension. In other words, the comprehension system draws on a production-based emulator. This emulator enables rapid comprehension and, at the same time, helps listeners deal with noisy input.

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