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PAPER

The development of sentence interpretation: effects of perceptual, attentional and semantic interference

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Abstract

How does the development and consolidation of perceptual, attentional, and higher cognitive abilities interact with language acquisition and processing? We explored children's (ages 5–17) and adults' (ages 18–51) comprehension of morphosyntactically varied sentences under several competing speech conditions that varied in the degree of attentional demands, auditory masking, and semantic interference. We also evaluated the relationship between subjects' syntactic comprehension and their word reading efficiency and general 'speed of processing'. We found that the interactions between perceptual and attentional processes and complex sentence interpretation changed considerably over the course of development. Perceptual masking of the speech signal had an early and lasting impact on comprehension, particularly for more complex sentence structures. In contrast, increased attentional demand in the absence of energetic auditory masking primarily affected younger children's comprehension of difficult sentence types. Finally, the predictability of syntactic comprehension abilities by external measures of development and expertise is contingent upon the perceptual, attentional, and semantic milieu in which language processing takes place.

Introduction

Children's syntactic development is often characterized as a rapid and relatively effortless process of establishing or fixing 'parameters' for a finite set of syntactic rules (Chomsky, 1980; Caplan & Waters, 1999; Crain & Pietroski, 2001; Foder, Bever & Garrett, 1974; Grodzinsky, 2000; Pinker, 1994; van der Lely, 2005). This approach emphasizes the child's early and fast-emerging competence in computing the symbolic relations between syntactic cues, and often relegates to 'performance' the role auditory perception and attentional control plays in complex language comprehension. In contrast, emergentist (MacWhinney, 1999) or connectionist (Thomas & Karmiloff-Smith, 2003) approaches tend to emphasize slower-emerging interactions between perceptual, cognitive, and linguistic processes over development. On such accounts, the processing of language is not carried out by language-dedicated modules; rather, language is inextricably enmeshed with 'lower-level' sensorimotor processes. Here, patterns of behavior that may appear rule-governed instead emerge through the interaction of acoustical, phonological, lexical, and syntactic cues (Monaghan, Chater & Christiansen, 2005). The development of language therefore involves not just acquiring words and grammatical structures but also developing and refining a range of auditory and attentional abilities throughout childhood and into adolescence. This is in marked contrast to the 'continuity hypothesis' whereby children attain syntactic mastery around 4 to 5 years of age – see Tomasello, 2000, for an overview and critique. Accordingly, recent research suggests that the successful acquisition of language may be contingent upon the development of fine motor and auditory skills (Alcock, Passingham, Watkins & Vargha-Khadem, 2000a, 2000b; Bishop, 2002; Briscoe, Bishop & Norbury, 2001; France, Rosner, Hansen, Calvin, Talcott, Richardson & Stein, 2002; Hill, Hogben & Bishop, 2005), as well as on domain-general attentional processes (Smith, Jones & Landau, 1996). Deficits in motor and auditory abilities and attentional control have been implicated in

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a number of developmental language disorders, including dyslexia (Ramus, 2003) and Specific Language Impairment (Benasich & Tallal, 2002; Bishop, 2005; Bishop & McArthur, 2004; McArthur & Bishop, 2005; Mengler, Hogben, Michie & Bishop, 2005). However, it is vital to note that there is still much debate about the ubiquity of these non-linguistic deficits in dyslexia and language impairment, and whether such non-linguistic skills play a causal role in developmental language disorders (Bishop, Adams, Nation & Rosen, 2005; Bishop, Adams & Norbury, 2006; Halliday & Bishop, 2005; Norbury, Bishop & Briscoe, 2002; van der Lely, Rosen & Adlard, 2004).

Recent domain-general accounts of adult aphasic language disorders have similarly suggested that perceptual and attentional abilities remain critical to language comprehension in the adult. Indeed, some aspects of language processing may be especially vulnerable to different types of sensory or cognitive disturbance (Aydelott Utman, Blumstein & Sullivan, 2001; Blumstein, Milberg, Brown, Hutchinson, Kuroeski & Burton, 2000). Evidence for the role of perceptual and attentional factors in language comprehension is not limited to populations with endogenous language disorders. Studies of healthy adults' language comprehension under conditions of cognitive and/or perceptual 'stress' have demonstrated that neurologically normal individuals show patterns of interference similar to those observed for aphasic patients (Aydelott & Bates, 2004; Davis & Johnsrude, 2003; Moll, Cardillo & Aydelott Utman, 2001; Scott, Rosen, Wickham & Wise, 2004). (Cognitive or perceptual stressors are additional processing loads that simulate the impact of brain damage or disorder.) Hayiou-Thomas, Bishop and Plunkett (2004) recently extended this approach to children, demonstrating that verb but not noun morphology was particularly affected by processing stressors for 6-year-olds, a response profile similar to that seen in children with Specific Language Impairment (SLI).

Why are some sentences harder to understand than others?

One explanatory framework for understanding 'selective' syntactic deficits is based on the predictions of the Competition Model of sentence processing (Bates, Devescovi & Wulfeck, 2001; Bates & MacWhinney, 1987). This interactive activation model envisages aspects of language comprehension as a statistical task, where the development of 'rule-like' behavior occurs through a process of establishing the validity and reliability of competing linguistic cues. In English, the most reliable cues to *agency* ('who is doing what to whom') are in the word or constituent order – that is, the relative position of the subject, verb, and object in an utterance.[1] However, some of these cues to agency are less 'available' than others – for instance, they may occur relatively infrequently – and thus may incur an additional processing cost.

Following on previous work, a recent study by Roland, Dick and Elman (2006) has shown that the relative frequency of constituent orders in English varies considerably. By far the dominant order is subject-verb(-object) (SV(O)) (e.g. 'the dog is biting (the cat)'). Across discourse registers, Roland *et al*. showed that 85% or more of verbs were preceded by the subject of that verb. Thus, utterances that use this word order cue should incur a relatively low cost in terms of processing resources, and should be quite accurately comprehended even in aphasia or under 'cognitive stress'. Additionally, because representations are distributed in the Competition Model, language structures that share this underlying word order or 'microstructure' (i.e. higher-dimensional regularities and structure) should also incur a low processing cost. For example, an English subject cleft sentence (e.g. 'It's the dog that is biting the cat') should have relatively high microstructural frequency inherited from active sentences by virtue of the shared SVO word order, even though subject cleft sentences themselves have very low absolute frequency (Dick & Elman, 2001; Roland *et al*., 2006). Conversely passives (e.g. 'the cat is bitten by the dog') and particularly object clefts (e.g. 'it's the cat that the dog is biting') have low absolute or 'token' frequency as well as low microstructural frequency (Roland *et al*., 2006). Consequently, the Competition Model predicts that interpretation of object cleft and passive sentences should be disproportionately affected under language breakdown or stress relative to subject cleft and active sentences.

These predictions are supported by studies of adult aphasic patients hearing non-degraded English sentences, as well as normal adults listening to speech under conditions of perceptual degradation and/or increased attentional demand (Dick, Bates, Wulfeck, Utman, Dronkers & Gernsbacher, 2001). In the case of normal adults under cognitive stress, performance on object cleft and passive sentences remains relatively robust in the presence of a single stressor (e.g. perceptual degradation alone), whereas these sentences are much more vulnerable than active and subject cleft sentences to a combination of stressors (e.g. spectral degradation combined with speeded speech rate). This pattern of results suggests that the consolidation of language function in the adult system may protect some complex sentence types from

[1] Note that in some cases the 'surface' grammatical subject and object do not map onto the agent and patient roles (or 'deep subject and object'); an example of this is the passive construction.

disruption, but that these structures are nevertheless subject to breakdown when multiple levels of processing are affected.

In addition to the findings for normal adults, the relatively few studies of typically developing children (ages 5–17 years) that do exist have shown that, across the full age range – including adolescence (Berman, 2004; Nippold, Hesketh, Duthie & Mansfield, 2005) – children gradually become faster and more accurate at interpreting and producing complex sentences, as well as in detecting grammatical violations in these sentences (Wulfeck, 1993; Wulfeck, Bates, Krupa-Kwiatkowski & Saltzman, 2004). This incremental process of development is particularly pronounced for low frequency (absolute and microstructural) sentence types (i.e. object clefts and passives – Bever, 1970; Dick, Wulfeck, Krupa-Kwiatkowski & Bates, 2004; Slobin, 1966; Turner & Rommetveit, 1968).

Of course, frequency of occurrence is far from being the sole determinant of cue reliability and cost. For instance, in English, subject–verb agreement cues to agency are very frequent, but not particularly reliable or easy-to-perceive sources of information about who is doing the action in the sentence. (Contrast this with Italian, where subject–verb agreement is a rich and reliable cue to agency, unlike word order – Bates, Wulfeck & MacWhinney, 1991.) Indeed, English speakers' performance is little affected by the presence of these agreement cues, although they allow for a small but significant improvement in accuracy in comprehending more difficult sentence types, particularly in younger children (Bates, MacWhinney, Caselli, Devescovi, Natale & Venza, 1984; Dick *et al*., 2004). This suggests that in the absence of a strong cue, young children use multiple weak cues, although these weak cues may be challenging for them to use (Wulfeck *et al*., 2004). On passive sentences, the presence of agreement cues actually leads to a reduction in performance, possibly because noun–verb agreement ties the verb to the patient and not the actor, as in the other sentence types. Further evidence comes from the performance of language-impaired children and children with focal lesions (Dick *et al*., 2004), who showed a particular deficit in the comprehension of object cleft and passive sentences. Interestingly, in Dick *et al*. (2004), agreement cues facilitated language-impaired (LI) children's responses for some sentence types (e.g. object clefts), and sped up reaction times for subject cleft sentences. However, as noted in a recent overview by Rice, Warren and Betz (2005), such agreement cues (and morphological cues more generally) pose a serious challenge to children with language impairments, and serve as a marker of particular delays in LI children's language development.

One recent approach investigating the processes involved in syntax comprehension compares children's and adults' eye movements to ambiguous 'garden path' sentences, such as *Put the frog on the napkin in the box*. By allowing different linguistic and referential cues to guide disambiguation of the sentential meaning, it is possible to pull apart the contribution of these cues to sentence comprehension over development. Trueswell and colleagues have found that whereas adults and 8-year-old children integrate referential and lexical/syntactic information to constrain their interpretation of a sentence, 5-year-old children appear to rely on the lexical/syntactic information (Trueswell, Sekerina, Hill & Logrip, 1999). However, as with the other experimental paradigms mentioned above, this change to using more referential cues does not occur suddenly, with 5-year-olds' eye movements indicating an increasing responsiveness to referential information (Snedecker & Trueswell, 2004). Similarly, whether children use referential cues or not appears to depend on the biases of the specific verb used. For instance, the verb *put* strongly biases the interpretation in favor of a verb-phrase attachment. Also, children's use of contextual or contextual and structural cues depends on whether a production or comprehension paradigm is used (Hurewitz, Brown-Schmidt, Thorpe, Gleitman & Trueswell, 2000).

Trueswell and colleagues interpret these results as evidence for a constraint-based lexicalist model of sentence comprehension (in many ways a descendant of the Competition Model), whereby multiple syntactic, lexical and contextual probabilistic cues are integrated simultaneously to arrive at the interpretation of a sentence (MacDonald, Pearlmutter & Seidenberg, 1994; Trueswell & Tanenhaus, 1994). According to this account, developmental changes in sentence comprehension are incremental and reflect changes in the information children have built up about the reliability of different cues.[2]

Taken together, the results of studies on children's complex sentence interpretation offer insight into the nature of morphosyntactic comprehension across the lifespan. These findings demonstrate that syntactic comprehension ability emerges gradually over the course of development, and that less frequent, more demanding linguistic structures take longer to acquire than structures that are more frequently encountered. Furthermore, complex sentence types such as passive and object cleft sentences are more vulnerable to disruption due to brain injury, language impairment, and exogenous cognitive stress than

[2] See Clahsen and colleagues (e.g. Clahsen & Felser, 2006) for an alternative explanation of some of these data, framed in terms of the 'continuity' hypothesis, with developmental changes in performance interpreted as resulting from changes in verbal working memory.

are active and subject cleft sentences. Once established, the adult language system is relatively resistant to cognitive stress. However, when multiple sources of disruption are combined (e.g. both perceptual and attentional stressors), the performance of normal adults on passive and object cleft sentences is typically severely compromised.

Cognitive and perceptual stressors: drama in real life

While the presentation of two or more types of interference during language comprehension may appear to represent an extreme example of cognitive stress, such disruption is routinely encountered in everyday listening situations. Most real world speech comprehension takes place in non-ideal noisy and distracting settings, including the classic 'cocktail party' environment (or typical elementary school classroom) where multiple talkers are speaking simultaneously. Although it has long been recognized that we can attend selectively to one among many competing voices (Broadbent, 1958; Cherry, 1953), competing speech makes language comprehension more difficult by diverting attention from the target speech signal, energetically masking the perceptual information associated with the target signal, and introducing conflicting semantic content (Moll *et al.*, 2001). Listeners can isolate an individual voice in a multitalker environment by focusing on its perceptual characteristics (i.e. the distinctive acoustic properties associated with differences in vocal quality, pitch and vocal tract length; Brungart, 2001; Darwin & Hukin, 2000; Bregman, 1990; Brokx & Nootebaum, 1982) and its spatial location (i.e. differences in the timing and intensity of the acoustic signal as it reaches the different ears; Cherry, 1953; Darwin & Hukin, 2000; Drennan, Gatehouse & Lever, 2003; Freyman, Balakrishnan & Helfer, 2001; Hawley, Litovsky & Culling, 2004). Nevertheless, semantic content from a non-selected signal can still draw attention away from the attended voice (Conway, Cowan & Bunting, 2001; Wood & Cowan, 1995). Thus, compensating for the perceptual and attentional interference from competing speech may place excessive demands upon the listener's processing resources, resulting in the disruption of sentence comprehension.

Such demands may have a particularly acute impact on children's language processing, given that their ability to segregate and attend to different aspects of the auditory stream continues to develop into adolescence (Hiscock & Kinsbourne, 1980). Indeed, the morphology of auditory evoked potentials to simple clicks and tones does not reach a steady state until at least late adolescence, suggesting that there is considerable fine-tuning of auditory perception throughout childhood and into early adulthood (Ceponiene, Rinne & Naatanen, 2002; Ceponiene, Lepisto, Soininen, Aronen, Alku & Naatanen, 2004; Ponton, Eggermont, Kwong & Don, 2000). Similarly, Sanders, Stevens, Coch and Neville (2005) showed that while the auditory evoked waveforms of 3–5-year-old children reflect the successful allocation of spatial auditory attention, the latency and polarity of these waveforms was not adult-like in a 6–8-year-old sample. In even older children (ages 9–13), Ceponiene *et al.* (2004) found that while many auditory-related electrophysiological components were adult-like, the distribution of the component thought to index an auditory attentional shift (the IP3a) was not.

One auditory skill where children show some early proficiency is in the use of spatial and spectral cues to segregate and attend to different speakers in a complex auditory scene. For instance, Litovsky (2005) reported that children's performance in a free-field speech intelligibility task benefited from a spatial 'release from masking' to the same extent as adults. However, using a different paradigm, Wightman, Callaghan, Lutfi, Kistler and Oh (2003) showed that preschool children's ability to detect a simple tone in one ear was seriously compromised by the presence of a complex noise distractor in the other ear, whereas adults' performance was completely unaffected by the contralateral distractor. The developmental trajectory of this 'release from informational masking' was relatively prolonged and marked by considerable individual differences. Following up on this study, Wightman and Kistler (2005) showed that an additional talker of the same gender in the same ear exerted considerably more informational masking of understanding spoken commands in even older children and adolescents relative to adults. Litovsky (2005) also found that children's speech comprehension was considerably more affected than adults' by the energetic (or 'perceptual') masking imposed by multiple competing speakers or a noise mask.

In summary, the current literature suggests that children's auditory perceptual and attentional competence undergoes a long and drawn-out progression into adulthood, with considerable fine-tuning with age. Moreover, although children can use spectral and spatial information to disambiguate speakers and aid comprehension, their auditory attentional abilities are far from fully developed, being markedly more susceptible to disruption than adults.

Not only do children have less efficient auditory processing than adults, but they have also had considerably less experience with language in general. This is in part reflected in the size of children's vocabularies which, during the school years, increase by an estimated 3000 words per year, albeit with considerable individual variation (see Graves, 1986, for a review). Similarly, children have considerably less exposure than adults to written texts, which tend to contain more complex syntactic constructions than spoken language (Roland *et al.*, 2006). The relative occurrence of complex and simple syntactic constructions in a child's linguistic environment may have a real effect on learning. Huttenlocher, Vasilyeva, Cymerman and Levine (2002) have shown that the proportion of complex syntactic structures produced by a child's teacher predicts how well the child herself will use and comprehend difficult syntactic constructions, above and beyond what is predicted by chronological age alone.

Other non-linguistic and non-auditory-specific skills may also come into play in language comprehension. For example, basic 'speed of processing' measures such as reaction time have been shown in some studies to be significant predictors of language delay or deficit (for instance, Miller, Kail, Leonard & Tomblin, 2001; Schul, Stiles, Wulfeck & Townsend, 2004). Such individual differences in overall language exposure and non-linguistic processing speed may interact with children's level of auditory attentional development in determining their capacity to comprehend complex linguistic constructions under difficult conditions.

The present study

We set out to tease apart the individual effects of attentional, semantic and perceptual interference in the acquisition and refinement of complex spoken language comprehension in school-age children and adults. As these abilities develop and become more fine-tuned over childhood and into adulthood, we would of course expect spoken language comprehension to be increasingly robust to interference. However, by observing when (and whether) children become resistant to different types of interference, we can begin to gauge the involvement of such perceptual, attentional and semantic processes in language comprehension.

In other words, we expected that the ability to comprehend complex sentences in the face of cognitive stressors would not just increase linearly with age, but rather would depend on the interplay of a combination of sentence difficulty and task difficulty as well as age. Given previous studies (e.g. Dick *et al.*, 2001, 2003, 2004), we expected that cognitive stressors would particularly challenge comprehension of harder sentences (i.e. sentences with non-canonical structure), and disproportionately so for young children. Furthermore, we anticipated that attentional, perceptual and semantic abilities would approach adult-like competence at different points on the developmental trajectory. Consequently, the age that children reach adult-like comprehension levels will vary for different interference conditions. Based on the findings of Litovsky (2005; discussed above), we expected that all but the youngest children's syntactic comprehension would largely be robust to non-perceptual interference (i.e. spatially segregated interference). We also expected that disruptive effects of competing semantic information on syntactic comprehension would be most evident when combined with perceptual interference (Moll *et al.*, 2001).

The present experimental design, which built on Dick *et al.* (2001, 2003, 2004), contrasted variations in word order (SVO, OSV, OVS) in four sentence types while controlling for a number of other potential cognitive confounds like memory load and semantic relatedness. For example, subject cleft (SVO) and object cleft (OSV) sentences have the same number of words, sentence lengths, lexical semantics, signal-to-noise ratio with competing sounds, and so forth. Thus, differential performance in different conditions of the experiment (i.e. across different sentence types, different cognitive stress conditions and different ages) will reflect differences in syntactic comprehension.

In the present study, we modulated the type of attentional, perceptual, and semantic interference with four different competing speech conditions. The conditions were organized, hierarchically, as follows:

1. The different ear/backwards speech condition (DfBk) reflects attentional interference alone (the effect of distracting speech-like noise without semantic content in the absence of energetic perceptual masking).
2. The different ear/forward speech condition (DfFd) reflects combined attentional and semantic interference.
3. The same ear/backward speech condition (SmBk) reflects combined perceptual interference and attentional interference (energetic masking by a distracting speech-like noise without spatial separation of the two signals).
4. The same ear/forward speech condition (SmFd) reflects a combination of all three types of interference (perceptual, attentional, and semantic).

Specific predictions

In general, we predicted that expertise with the less frequent, more demanding sentence types (i.e. object cleft and passive sentences) would be achieved later in development than for more frequent active and subject cleft sentences. Further, as an 'immature' language system may be particularly dependent upon detailed perceptual information and intact attentional resources, we predicted that competing speech would disrupt syntactic comprehension more easily in children than in adults. Moreover, we predicted that different types of interference would manifest themselves in the following ways over development:

Prediction 1: Attentional interference

Since younger children have previously been shown to be relatively resilient to spatially segregated interference (Litovsky, 2005, but cf. Wightman *et al*., 2003), we expected that 'pure' attentional (i.e. non-perceptual) interference would manifest itself only in younger children's comprehension of the hardest, least frequent sentence structures. More concretely, we predicted that younger children's performance with object clefts and passives should be slightly less accurate in the DfBk (different ear, backwards speech) condition relative to the no-interference condition. This effect is expected to largely or completely disappear with age, as children's ability to direct auditory spatial attention reaches asymptote (Wightman *et al*., 2003).

Prediction 2: Perceptual interference

We expected that the youngest children's sentence comprehension would be particularly vulnerable when competing and target speech streams are presented in the same auditory channel (i.e. to the same ear; Litovsky, 2005; Wightman & Kistler, 2005). Such perceptual interference should thus challenge younger children's comprehension of all sentence types. Given adults' expertise with auditory stream segregation and more complex language structures, we predicted that perceptual interference (i.e. SmFd and SmBk conditions) would be relatively ineffectual in adults, affecting only hard sentence types like passives and object clefts. However, considering the long developmental trajectory of these auditory and language abilities, we expected that the path to such mastery would extend throughout childhood and early-to-mid adolescence.

Prediction 3: Semantic interference

Given previous results (Moll *et al*., 2001), we predicted that evidence of semantic interference would be most marked in the combined SmFd (same ear, meaningful speech) condition, where the simultaneous effects of perceptual masking, increased attentional demand, and semantic interference should selectively disrupt the more complex sentence types. Moreover, any evidence of semantic interference in adults should only be apparent in this combined stressor condition.

Prediction 4: Agreement cues

According to the Competition Model, the extent to which a child uses agreement cues (which have weak cue validity in English) depends on the availability of other cues, such as word order. We therefore predicted that the presence or absence of agreement cues would only affect sentence comprehension when word order is a relatively costly cue (i.e. in non-canonical sentences) and agreement cue validity is high. Thus, the effect of agreement cues should only be seen for object cleft sentences rather than the canonical SVO sentence types or passives (where agreement cue is more of a hindrance than a help). In addition, since language impaired children appear to rely on agreement cues (possibly using a coalition of multiple weak cues; Dick *et al*., 2004), we predicted that children's reliance on agreement cues on object cleft accuracy would increase in the most challenging competing speech conditions.

Prediction 5: Age, speed of processing and TOWRE/SWE

A child's exposure to and expertise with more formal and structured registers of English may influence how well s/he will comprehend complex syntactic forms. The child's (or adult's) basic 'speed of processing' may also contribute to proficiency in syntactic comprehension. As suggested in the introduction, both these factors may be more predictive of the development of syntactic comprehension abilities than simple chronological age alone. In order to test this hypothesis, we used subjects' word reading efficiency (TOWRE; Torgensen Wagner & Rashotte, 2001) and reaction times to simple sounds as additional predictors of syntactic comprehension.

Method

Complex sentence interpretation

Participants

A total of 61 adults and 348 children completed the study. The children ranged from 4:8 to 17:11 years. The adults ranged from 18:0 to 51:11 years, with a mean age of 32:4 years. All participants were recruited and tested as part of the 'Live Science' programme at the National Museum of Science and Technology, London. All participants were native British English speakers. Participants were screened for any present or past hearing problem. Each participant who met the selection criteria was randomly allocated to one of five different competing speech conditions (see Table 1 for *N* per cell).

Stimuli

All stimuli were taken from a complex sentence interpretation task used in previous studies (Dick *et al*., 2001,

Table 1 *Subjects in each condition and age group. DfBk = different ear, backwards speech; SmBk = Same ear, backwards speech; DfFd = Different ear, forward speech; SmFd = Same ear, forward speech; NoComp = no competing speech*

	DfBk	SmBk	DfFd	SmFd	NoComp	Total
4 to 6	8	9	7	13	18	55
7 to 8	17	17	18	11	10	73
9 to 10	17	17	18	18	16	86
11 to 12	17	14	19	15	14	79
Over 13	21	25	21	23	26	116
Total	80	82	83	80	84	409

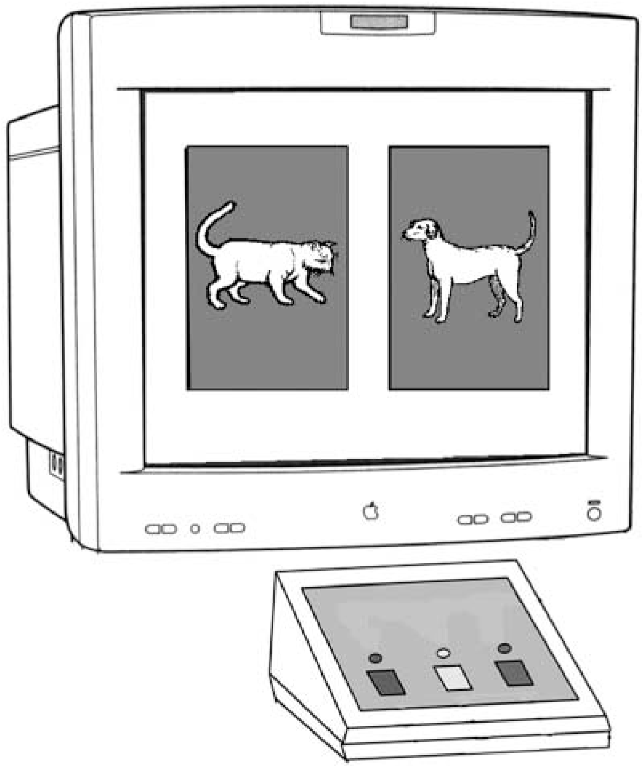

Figure 1 *An illustration of the experimental setup.*

2003, 2004). Visual stimuli were 3 in. by 2 in. digitized black-and-white line drawings taken from several picture databases (Abbate & LaChappelle, 1984a, 1984b; Snodgrass & Vanderwart, 1980). The pictures were displayed on a VGA color monitor. Each drawing was embedded in a solid grey rectangle over a white background; drawings were presented in pairs determined by sentence content and projected to the left and right sides of the monitor (see Figure 1 for example drawings as presented on the monitor). Auditory sentence stimuli consisted of 96 sentences representing four syntactic structures: active ('The dog is biting the cow'), subject cleft ('It's the dog that is biting the cow'), object cleft ('It's the cow that the dog is biting'), and passive ('The cow is bitten by the dog'). Each of these pairs was pseudo-randomly assigned to one of four inflectional paradigms: (1) subject and object inflected in singular, verb agrees with both; (2) subject singular, object plural, verb agrees with subject; (3) subject plural, object singular, verb agrees with subject; (4) subject plural, object plural, verb agrees with both. Each level of the Sentence Type was thereby represented by 24 exemplars, half of which contained a cue to agency via subject–verb agreement (inflections (2) and (3)), and half of which contained no agreement cue to agency (inflections (1) and (4)) – see Table 2 for example sentences. Ninety-six sentences were then divided into two sets of 48, each containing equal numbers of Sentence Type and Subject–Verb Agreement Cue. Participants were randomly allotted one of the two lists.

The sentence stimuli and the names of each individual animal were produced by a male native speaker of British English and recorded onto digital audio tape (DAT) in an Industrial Acoustics 403-A audiometric chamber with a TASCAM DA-P1 DAT recorder and a Sennheiser ME65/K6 supercardioid microphone and pre-amp at gain levels between –6 and –12 db. The recorded stimuli were then digitized via digital-to-digital sampling onto a Macintosh G4 computer via a Digidesign MBox using ProTools LE software at a sampling rate of 44.125 kHz with a 16-bit quantization. The waveform of each sentence and animal name was then edited, converted into a 16-bit 44.125 kHz mono sound file in SoundEdit 16, and saved in System 7 format. The sentences were used as test stimuli in the *no competing speech* condition, and the animal names were used to label the picture stimuli that preceded the test sentences.

A passage from the introduction to a statistics textbook (Maxwell & Delaney, 2000) was recorded on the same equipment and under the same conditions described above by a different male native speaker of British English. This recording was then used for both the forward and backward competing speech conditions. In the *forward competing speech condition/different ear*, stereo versions of the original mono sentence files were generated in which the waveforms of the target sentences were inserted onto one channel of the stereo sound file, and segments of competing speech of the same duration as the target sentences were excised at random and inserted onto the other channel, using SoundEdit 16 waveform editing software. Both target and competing speech signals were normalized to a root mean squared amplitude of 70 dB using Praat software, such that the average signal-to-noise ratio was zero (0) dB for stimuli containing competing speech. In the *backward competing speech condition/*

Table 2 *Example sentences corresponding to the 4 different sentence types, both with and without agreement cues. Noun and verb number morphemes are underlined*

Sentence type	Example sentences
Active	The dog_ is kicking the cat.
Active with agreement cue	The dogs are kicking the cat.
Subject Cleft	It's the dog_ that is kicking the cat.
Subject Cleft with agreement cue	It's the dogs that are kicking the cat.
Passive	The cat_ is kicked by the dog.
Passive with agreement cue	The cat_ is kicked by the dogs.
Object Cleft	It's the cat that the dog_ is kicking.
Object Cleft with agreement cue	It's the cat that the dogs are kicking.

different ear, the competing speech signals in the forward competing speech condition were time-reversed using the 'backwards' function in SoundEdit 16. In the *forward and backward competing speech conditions/same ear*, the target and competing speech stimuli from the different ear conditions were mixed in SoundEdit 16 and presented simultaneously on one channel of the stereo sound file; the other channel was left blank. All the stimulus files were converted into 16-bit 44.125 kHz stereo files in SoundEdit 16 and saved in System 7 format.

Procedure

Before participants were presented with the main sentence interpretation task they were given a short test to establish their baseline reaction time (RT) to sounds presented in different auditory channels. The baseline measure consisted of 32 'ping' sounds, each 0.3 seconds long, which were adapted from the alert sounds native to Mac OS 10.3. Participants pressed either the left or right button on a response box corresponding to the ear in which they heard a sound. Participants were asked to press the button as fast as they could with the index finger of their dominant hand.

In the sentence interpretation task, participants were told that they would see two pictures of animals, hear their names, and then hear a sentence featuring the animals. They were instructed to press the button on the same side as the animal doing the bad action. In the competing conditions, participants were told they would hear someone else speaking at the same time, but to concentrate on the sentence about the animals. These instructions were repeated on screen and heard over the headphones. For younger children, the experimenter modeled several example trials before the start of the experiment. Participants completed five practice trials before moving on to the main part of the experiment.

Each trial consisted of two drawings of animals, presented simultaneously, on the left and right side of the screen. The names of the animals were presented auditorily in a random order, followed by the test sentence, with an interval of 1 second between auditory events. Both the first animal named and the position of the subject animal (left or right) was counterbalanced across participants. Following the participant's response was a 2.8 second interval before presentation of the next sentence. If a participant failed to respond, the next sentence was presented 8 seconds after onset of the previous sentence. The order of presentation of the 48 sentences was fully randomized for each participant. In the competing speech conditions, the ear of presentation of the target sentence (left or right) was counterbalanced across participants.

The experiment was presented on Macintosh G3 and G4 laptop computers using SuperLab software, v. 1.77. The stimuli were presented through Sennheiser HD 25–1 headphones. The participants were tested either in a quiet room, or at the Live Science exhibit at the Science Museum, London. This exhibit was in a relatively quiet area of the museum, three-quarters enclosed. RTs and accuracy were recorded in SuperLab from a Cedrus USB response box.

Reading test

Most participants also took a standardized test of word reading, the Sight Word Efficiency (SWE) component of the Test of Word Reading Efficiency (TOWRE). This took place before the computerized component of the experiment. Sixteen participants did not take the TOWRE/SWE, including eight young children who were not sufficiently competent readers. The TOWRE/SWE was included to provide an alternative measure of a participant's language abilities. The TOWRE/SWE is a very reliable indicator of children's reading ability (as assessed by teacher ratings) and correlates with vocabulary size (Dale, Harlaar & Plomin, 2005). The TOWRE/SWE was especially appropriate for our setting because it could be administered to museum visitors in 3 minutes.

The TOWRE/SWE consists of two equivalently difficult lists of 104 English words. The lists are designed so that the words are increasingly difficult (as measured by word frequency and length) from the beginning to the end of each list. Participants were instructed to read through one of the two lists out loud as fast as they could. The experimenter recorded the number of words correctly read out in 45 seconds as well as the time remaining if the participant finished in less than 45 seconds. The raw TOWRE/SWE scores were used in all subsequent analyses.

Results

Participants were split into four age groups: 7–8, 9–10, 11–12, and over 13 years, as shown in Table 1. (Due to the small number of participants per condition in the 4–6 age group these participants are only included in ANCOVA analyses where age is a continuous variable.) All analyses of variance (ANOVAs) were run on mean correct response (CR) as the dependent variable. *Sentence type* (Active, Subject Cleft, Passive, or Object Cleft) and *noun–verb agreement cue* (present or absent) were within-subjects variables in the subject analysis, and between-items variables in the item analysis. *Semantic interference* (no competing speech, forward and backward competing speech) and *perceptual interference* (no competing speech, competing speech in a different auditory channel and in the same auditory channel as the target) as well as *age group* (as defined above) were between-subjects variables in the subject analysis and within-items variables in the item analysis. *F*1 statistics used subjects as the random factor, and *F*2 used items (the 96 individual sentence exemplars) as the random factor. All within-subject effects *p*-values were Geisser-Greenhouse (G-G) corrected (Geisser & Greenhouse, 1958). Levene's tests indicated that some ANOVAs violated the assumption of homogeneity of variance, thus affecting interpretation of the *F* statistics for between-subject effects. Because of this heterogeneity of variance in the dependent variables, combined with unequal sample sizes in different conditions, we have supplemented the between-subjects ANOVA results with Welch tests followed by Games-Howell post-hoc procedures – robust to homogeneity of variance violations even with unequal sample size (Howell, 1997). As initial analyses showed no significant effects of presentation ear, the results are collapsed over right and left ear conditions.

The relationship between age and performance over development is often best characterized by non-linear growth curves rather than straight lines. Therefore, we ran additional analyses following non-linear transformations of the participants' ages. Preliminary analyses revealed that a reciprocal transformation of children's age provided a close fit to the shape of our behavioral data over development. Importantly, this function explicitly models a non-linear, fast rise in performance with a longer tail to asymptote (i.e. an increasing first differential and a decreasing second differential), just as might be expected of the language development in children in this age group. Moreover, the reciprocal transformation allowed us to explicitly model potential ceiling effects in the data, revealing more subtle effects later in development. In general, continuous regressors should reveal more subtle effects than group analyses (Bates, Saygin, Moineau, Marangolo & Pizzamiglio, 2005; Zangl, Klarman, Thal, Fernald & Bates, 2005). We ran three types of linear regressions on the transformed data: (1) normal ordinary least squares linear regression; (2) robust regression (resilient to outliers with high leverage values); and (3) linear regression with robust standard errors (i.e. robust to heteroskedasticity). All regressions were run over all subjects, but were also *verified with analyses with children only (ages 4–17)*. Throughout the results section we distinguish simple chronological age (age) with reciprocally transformed chronological age (RecipAge).

General findings

As expected, we replicated the major findings from typically developing children reported in previous studies (e.g. Slobin, 1966; Dick *et al*., 2004), with significant main effects of age (i.e. increasing accuracy) and sentence type (i.e. a significant difference between easy versus hard sentences). Furthermore, there was a significant interaction between *sentence type* and *age group*, with easy sentences (Subject Clefts and Actives) showing adult-like accuracy earlier (around 7–8 years) than harder sentences (Object Clefts and Passives) where adult-like performance was first observed at around 9–10 years.

In addition to replicating previous findings, the current study also demonstrated a three-way interaction between *sentence type*, *age group* and *perceptual interference* for both subject and item ANOVA models (see Figures 2–5). Note, however, that there was no significant overall *sentence type* by *age group* by *semantic interference* interaction, suggesting that perceptual speech-like interference was a more important determinant of performance over age than was semantic interference. Due to the complexity of the experimental design, when investigating this three-way interaction, we considered only those effects treating the predictions detailed at the end of the introduction. (However, all ANOVA main effects and interactions are provided in Table 3 for the interested reader.)

Prediction 1: Attentional interference

We expected that any disruptive effect of attention independent of perceptual or semantic interference (i.e.

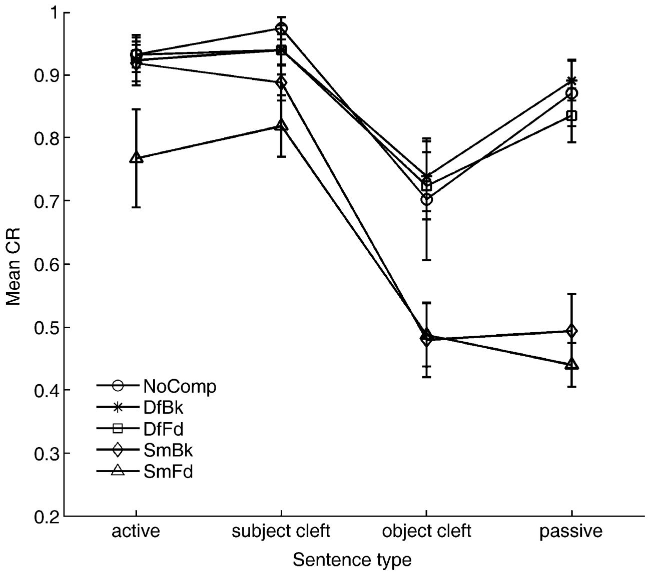

Figure 2 *Sentence type by condition for 7–8-year-olds.*

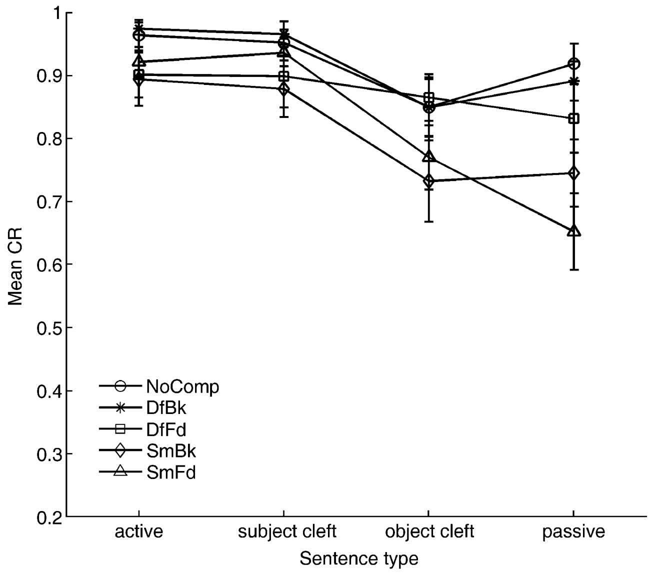

Figure 4 *Sentence type by condition for 11–12-year-olds.*

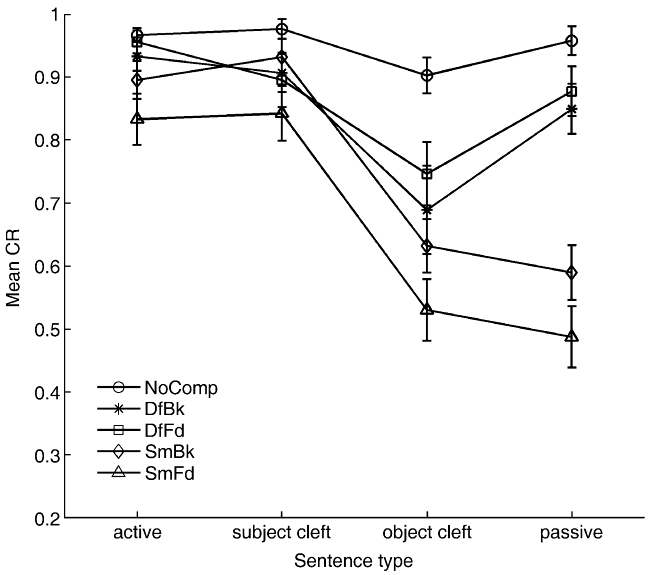

Figure 3 *Sentence type by condition for 9–10-year-olds.*

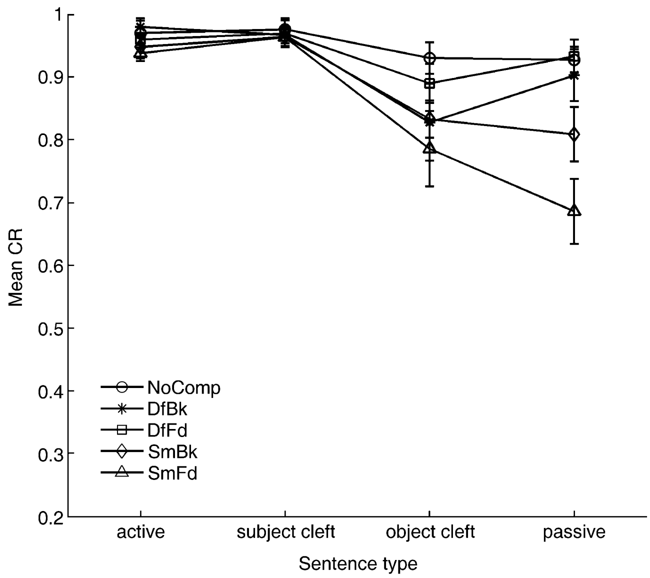

Figure 5 *Sentence type by condition for over-13-year-olds.*

the DfBk condition) would only be detectable for the younger children, and would be more pronounced in the difficult sentences (object clefts and passives). We thus compared comprehension accuracy for Easy and Hard sentences in DfBk and no-competing (No-comp) speech conditions within different age groups, using Welch tests. Unexpectedly, the youngest children (7–8 years old) performed equally poorly in both no-competing speech (overall 93% correct; chance was 50%) and DfBk (89%) conditions (Welch's test not significant for either sentence type group). It was not until 9–10 years that accuracy in the No-comp condition began to outstrip that in DfBk (Difficult sentences, Welch(1, 31) = 8.38, $p < .001$, Kruskal-Wallis test, $p < .05$; Easy sentences, Welch(1, 31) = 4.768, $p < .05$, Kruskal-Wallis test *ns*, $p > .05$)[3] – with performance in No-comp indistinguishable from adults. For 11–12-year-olds, the gap between DfBk and no-competing closed (i.e. no significant difference between DfBk and No-comp),

[3] Supplementary non-parametric Kruskal-Wallis tests were used because of the earlier-stated concerns regarding the non-normality of data distributions.

Table 3 *Main ANOVA (f1 is with subject as random effect; f2 is with sentence type as random effect)*

	f1		f2	
Age Group (AG)	$F(3, 334) = 13.801$	$p < .0001$	$F(3, 88) = 67.856$	$p < .0001$
Semantic (Sem)	$F(1, 334) = 8.205$	$p < .076$	$F(1, 88) = 10.186$	$p = .002$
Perceptual (Per)	$F(1, 334) = 68.055$	$p < .0001$	$F(1, 88) = 190.755$	$p < .0001$
Per*AG	$F(3, 334) = 4.645$	$p < .003$	$F(3, 264) = 18.246$	$p < .0001$
Sentence-type (Sent)	$F(3, 1002) = 165.78$	$p < .0001$	$F(3, 88) = 100.413$	$p < .0001$
Sent*Sem	$F(3, 1002) = 2.414$	$p = .08$	$F(3, 88) = 1.602$	$p = .195$
Sent*Per	$F(3, 1002) = 50.062$	$p < .0001$	$F(3, 88) = 32.266$	$p < .0001$
Sent*AG	$F(9, 1002) = 7.183$	$p < .0001$	$F(9, 264) = 6.484$	$p < .0001$
Sent*Per*AG	$F(9, 1002) = 2.559$	$p = .013$	$F(9, 264) = 2.604$	$p = .01$
Agreement (Agree)	$F(1, 334) = 2.743$	$p = .099$	$F(1, 88) = 0.053$	$p = .818$
Sent*Agree	$F(3, 1002) = 5.792$	$p = .001$	$F(3, 88) = 0.072$	$p = .975$
Sent*Agree*Per	$F(3, 1002) = 2.372$	$p = .079$	$F(3, 264) = 0.709$	$p = .549$
Sem*Per	$F(1, 334) = 2.234$	$p = .136$	$F(1, 88) = 9.068$	$p = .003$
Age*Sem*Per	$F(3, 334) = 1.376$	$p = .25$	$F(3, 264) = 9.284$	$p < .0001$
Age*Sem*Per*Sent	$F(9, 1002) = 1.397$	$p = .198$	$F(9, 264) = 2.024$	$p = .044$
		All other effects are non-significant in both f1 and f2 analyses		

with children in the DfBk condition achieving quasi-adult performance for difficult sentences. These results indicated that there was a transient effect of attentional interference on the development of sentence comprehension, one which is more marked for comprehension of difficult sentences.[4]

Prediction 2: Perceptual interference

We expected that when target and competing speech occurred within the same channel (i.e. perceptual interference), all participants would be affected for the hard sentences, but young children would be severely affected for all sentence types (including the easiest active and subject cleft sentences). As predicted, across *all* ages, hard sentences (object cleft and passives) were comprehended significantly worse in the same ear conditions (i.e. SmBk and SmFd) than in the no-competing speech condition (7–8-year-olds, Welch(1, 36) = 15.11, $p < .01$; 9–10-year-olds, Welch(1, 49) = 99.291, $p < .001$, 11–12-year-olds, Welch(1, 41) = 11.102, $p < .01$; over 13, Welch(1, 68) = 15.68, $p < .001$). In contrast, 11–12 and 13-up age groups showed no statistically significant differences between same and no-comp conditions for easy sentences, while younger children's comprehension of the easy sentences was markedly less accurate under perceptual interference than in the no-competing speech condition (7–8-year-olds, Welch(1, 36) = 9.734, $p < .01$; 9–10-year-olds, Welch(1, 49) = 13.64, $p < .01$), showing that age dramatically modulated susceptibility to non-spatially separated interference for easy sentence comprehension.

A more explicitly 'developmental' approach to analyzing these differences is to statistically compare the shape of the cross-sectional developmental trajectory over non-linearly transformed age. To test whether there is a reliable difference in the fit between same ear and different ear conditions, we compared the beta coefficients (slope) of the best fit equations for easy (active/subject cleft) and difficult (passive/object cleft) sentences using *t*-tests (Howell, 1997). (See Figures 6a–d for scatterplots showing individual datapoints and best-fit lines.) This approach revealed essentially what we had seen using our previous analyses. As with the ANOVAs above, we saw that the developmental trajectory to asymptote is significantly more prolonged in Same Ear than Different Ear conditions, particularly for difficult sentences (Ordinary Least Squares (OLS) regression, $t(321) = 4.00$, $p < .0001$; robust regression (RR), $t(321) = 3.97$, $p < .0001$; regression with Robust Standard Errors (RSE), $t(321) = 3.06$, $p < .01$).

Prediction 3: Semantic interference

We anticipated that semantic interference would be most evident when contrasting the two same ear conditions, with a superadditive decrement in difficult sentence comprehension from conjoint presentation of the *semantic* (meaningful speech) and the *perceptual interference* (same auditory channel) components. Unexpectedly, a Welch test of difficult sentence comprehension contrasting forward speech in the same ear (SmFd) with backward speech in the same ear (SmBk) indicated that there was at best a marginal effect of *semantic* interference for 9–10-year-olds (Welch(1, 33) = 3.090, $p < .088$), with no significant

[4] Although the younger children were not performing equivalent to adults, neither were they at or even close to floor. Therefore, if there were a strong effect of attention (in the absence of perceptual or semantic interference) we would have expected to observe it for the 7–8-year-olds. Indeed, we observed a significant *perceptual* interference effect for this age group, as noted below.

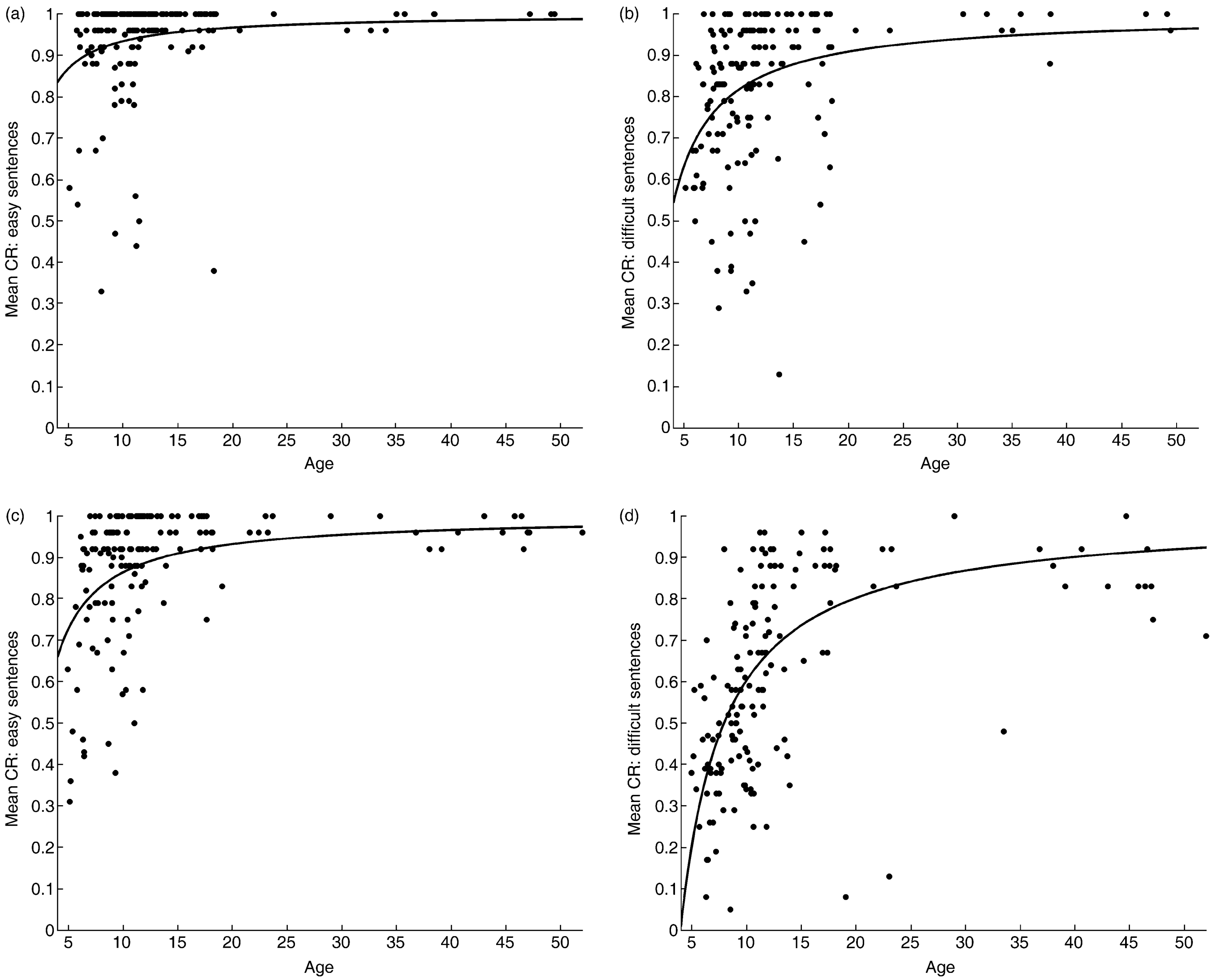

Figure 6 *Mean accuracy on easy sentences (i.e. subject cleft and active – 6a and 6c) and difficult sentences (object cleft and passive 6b and 6d) in Different ear (6a and 6b) and Same ear (6c and 6d) conditions.*

effect for any other age group. (Adult participants did show a numerical advantage in comprehending difficult sentences in the SmBk vs. SmFd condition, but this was only marginally significant for passive sentences (Welch(1, 42) = 3.30, $p < .077$), and thus should not be granted much import.) These unexpected results suggest that semantic interference has a relatively minor to negligible effect on the accuracy of syntactic comprehension in both children and adults. Similarly, we saw that the reciprocally transformed best-fit curves for the forward versus backward speech did not differ statistically – OLS, $t(321) = 0.39$, *ns*; RR, $t(321) = 0.094$, *ns*; RSE, $t(321) = 0.25$, *ns*; see Figures 7a and b – suggesting that the direct effect of semantic interference is too small to detect, if it is present at all. Indeed, we did not even observe this effect when comparing the 'superadditive' SmFd to the SmBk condition – OLS, $t(321) = 0.72$, *ns*; RR, $t(321) = 0.45$, *ns*; RSE, $t(321) = 0.80$, *ns*; see Figures 8a and b.

Prediction 4: Agreement cue

We predicted that a facilitatory effect of agreement cues should only be seen for object cleft sentences, and that children's reliance on agreement cues for object cleft accuracy would increase in the most challenging competing speech conditions. As predicted, agreement cues improved performance for the Object Cleft sentences only ($F(1, 394) = 6.91$, $p < .001$, repeated measure ANOVA

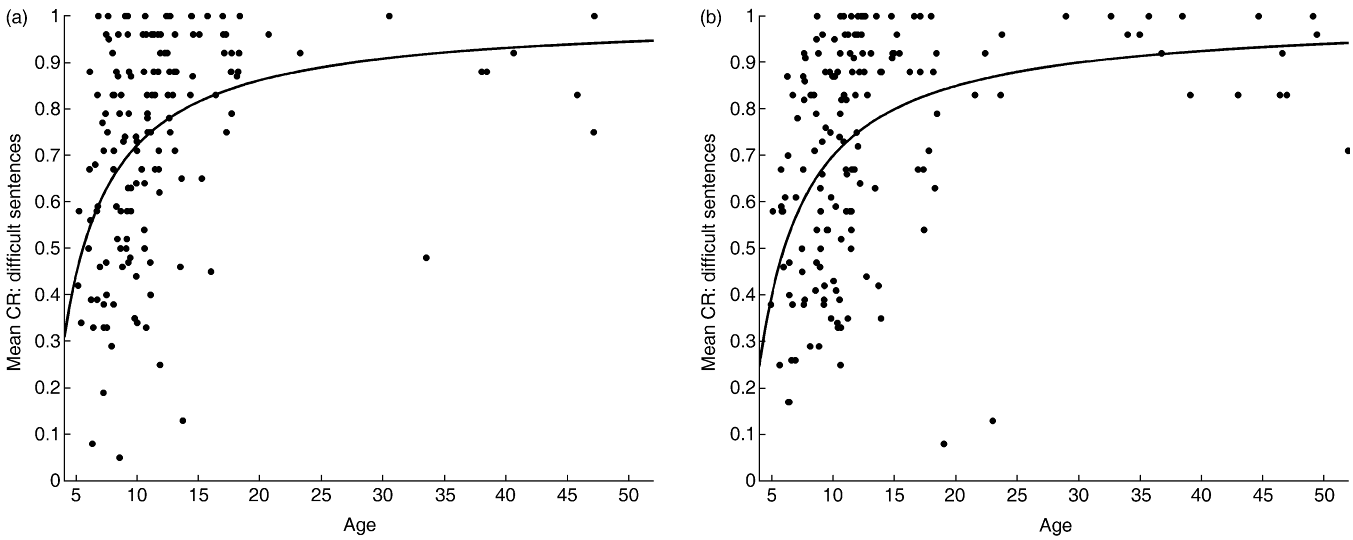

Figure 7 *Mean accuracy on difficult sentences (i.e. object cleft and passives) for Backwards (7a) and Forward speech (7b).*

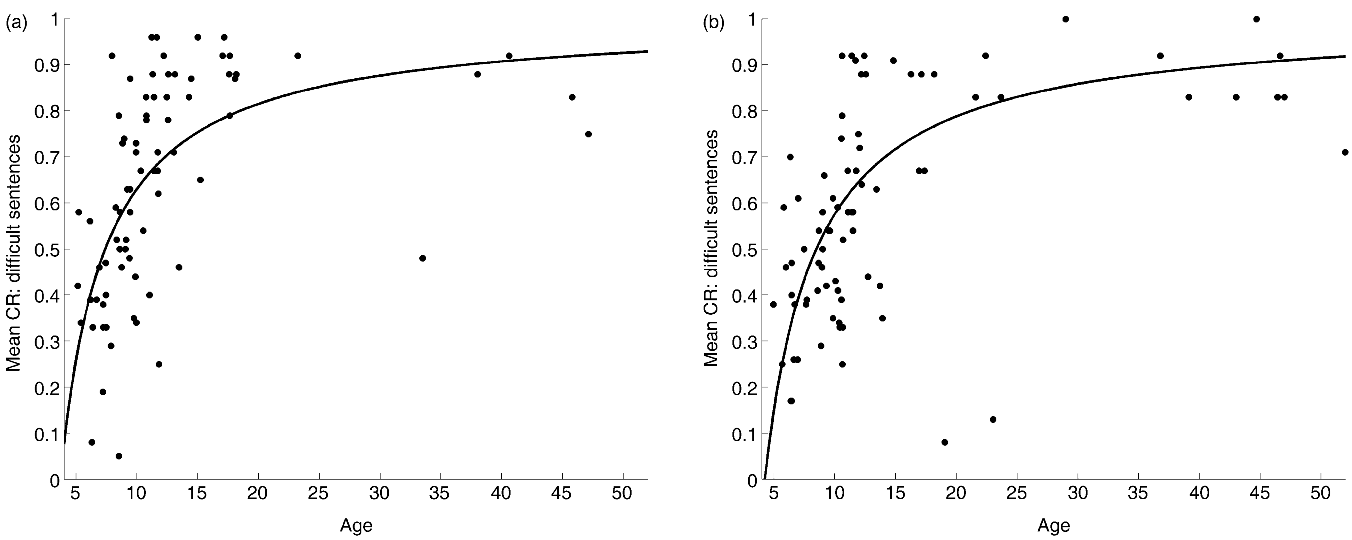

Figure 8 *Mean accuracy on difficult sentences (i.e. object cleft and passives) for Same ear/Backward speech (8a) and Same ear/Forward speech (8b).*

comparing object cleft accuracy with and without agreement cue – see Figure 9). Subsequent *t*-tests on object cleft sentences in each of the different interference conditions indicated that agreement modulated performance in the No-comp condition only ($t(1,65) = 4.36$, $p < .001$ – with Bonferroni correction for multiple pairwise comparisons). The presence of all other types of competing speech eliminated any significant agreement cue effect, in accordance with previous studies regarding the fragility of agreement cues in English for adult speakers (Blackwell & Bates, 1995; Dick *et al.*, 2003). However, in contrast to our predictions and findings in previous studies, there were no indications of increased agreement cue use in younger subjects, as reflected in the lack of *age group* × *agreement* or *age group* × *agreement* × *condition* interactions for object clefts.

Prediction 5: Age, speed of processing and TOWRE/SWE

As mentioned in the introduction, we anticipated that reciprocally transformed chronological age ('RecipAge'), general 'speed of processing' ('SP' – assessed using the baseline auditory response task), and overall reading

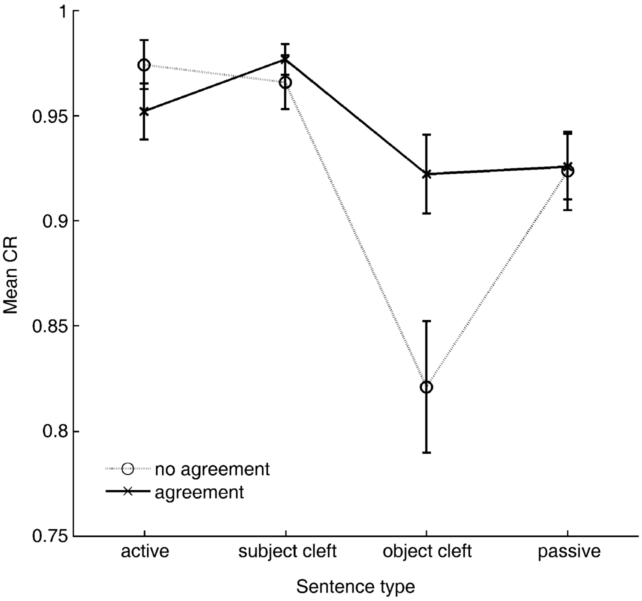

Figure 9 *Sentence type by agreement for the No-Competing speech condition.*

ability (assessed via TOWRE/SWE) would better predict sentence comprehension abilities than the reciprocal of chronological age alone, particularly for sentences with non-canonical word orders (i.e. passives and object clefts). We assessed these hypotheses by running three separate ANCOVAs with either RecipAge, general SP, or TOWRE/SWE score as the continuous variable; we then evaluated the 'goodness' of each predictor variable using hierarchical stepwise regression to establish unique variance accounted for by each predictor (see Table 4 for descriptive statistics of the different predictors). We anticipated that for the hard sentence types under the most challenging interference conditions, we would observe a considerably more elongated and stronger relationship between the different predictors and sentence comprehension accuracy than for the easy sentences and the less disruptive listening conditions. Furthermore, we expected that these effects would be more evident for the TOWRE/SWE and SP than for RecipAge.

Table 4 *Characterization of participants' age, reading test performance and speed of processing reaction time*

	N	Mean	Std Dev	Min	Max
Raw TOWRE/SWE	393	74.48	19.78	9	113
Standardized TOWRE/SWE[1]	302	111.12	11.84	75	145
Speed of Processing (in ms)	409	826.77	192.91	361.5	2019
Age	409	13.56	9.36	4.69	51.98

[1] Standardized TOWRE scores are for children only and were not used in regression analyses.

Table 5 *ANCOVA analyses with Reciprocal Age, SP or TOWRE*

Reciprocal Age (Age)	$F(1, 399) = 143.727$	$p < .0001$
Age*Perceptual (P)	$F(1, 399) = 16.902$	$p = .0001$
Sentence Type (ST)	$F(3, 1197) = 4.517$	$p < .0088$
ST*Age	$F(3, 1197) = 36.882$	$p < .0001$
ST*P	$F(3, 1197) = 23.172$	$p < .0001$
ST*P*Semantic (S)	$F(3, 1197) = 2.283$	$p = .096$
ST*P*Age	$F(3, 1197) = 2.452$	$p = .0808$
Speed of Processing (SP)	$F(1, 399) = 35.061$	$p < .0001$
SP*P	$F(1, 399) = 8.454$	$p = .0038$
Sentence Type (ST)	$F(3, 1197) = 3.473$	$p = .0279$
ST*SP	$F(3, 1197) = 17.325$	$p < .0001$
ST*SP*P	$F(3, 1197) = 2.346$	$p = .0916$
ST*S*P	$F(3, 1197) = 3.442$	$p = .0288$
ST*SP*S*P	$F(3, 1197) = 2.939$	$p = .0490$
TOWRE (T)	$F(1, 383) = 138.157$	$p < .0001$
Perceptual (P)	$F(1, 383) = 28.906$	$p < .0001$
T*P	$F(1, 383) = 8.772$	$p = .0032$
Sentence Type (ST)	$F(3, 1149) = 83.459$	$p < .0001$
ST*T	$F(3, 1149) = 36.136$	$p < .0001$
ST*P	$F(3, 1149) = 6.973$	$p = .0006$
ST*S*P	$F(3, 1149) = 3.114$	$p = .0388$
ST*T*S*P	$F(3, 1149) = 4.195$	$p = .0120$

Age, SP and TOWRE/SWE

When SP, TOWRE/SWE, and RecipAge were entered as continuous predictors with sentence type and competing speech condition in separate ANCOVAs (see Table 5), all three predictors showed a significant association with accuracy, as well as a significant interaction with sentence type. For all three predictors, the most variance explained was for the difficult sentences, i.e. the sentence types with the most infrequent underlying word order (Roland *et al.*, 2006).

Notably, for TOWRE/SWE – but not RecipAge or SP – we saw the same interaction with sentence type for a sub-ANCOVA run on participants aged 13 years or older (TOWRE/SWE × Sentence Type, $F(3, 312) = 7.242$, $p < .001$). This suggests that object cleft and passive comprehension (the hardest sentence types) has a particularly prolonged developmental trajectory, one associated more with overall language abilities than simple 'maturation' over time (also see Figure 6b and d).

Unique contributions

Although we see significant effects of RecipAge, SP and TOWRE/SWE, this may in part be due to the correlations between these three variables (SP vs. TOWRE/SWE, $r = -.531$; SP vs. RecipAge, $r = -.530$; TOWRE/SWE vs. RecipAge, $r = .822$). One way to disentangle the relative importance of the three variables as predictors of CR is to compare an index of the unique variation (adjusted R^2) explained by SP, RecipAge and TOWRE/SWE in robust regressions run on different conditions.

The unique variation accounted for by each of the three predictors was calculated by entering each variable at the final step of a hierarchical multiple regression model. This procedure indicated whether this unique contribution significantly improved the model fit.[5]

For Easy sentences in all conditions, no factor contributed discernible unique variance, nor was there significant predictive power of the shared variance underlying the three variables. (This is not so surprising since there is not a great deal of variance to account for, given the generally high accuracy levels.) For Hard sentences in the No-comp and Different Ear conditions, each factor also contributed little to no unique variance, but here the shared variance was considerably greater in its predictive power (adjusted $R^2 = 0.235$). Finally, two factors significantly predicted unique variance in subjects' accuracy for Hard sentences in Same Ear conditions. Interestingly, the patterns of unique variance distinguished between the two Same Ear conditions, despite the fact that they did not significantly differ in accuracy.

For the Same Ear/Backwards Speech condition, both TOWRE and RecipAge predicted unique variance (adjusted R^2 for: TOWRE/SWE = 0.202; RecipAge = 0.110). There was also considerable additional variance common to all three factors (adjusted $R^2 = 0.274$). For Hard sentences in the Same Ear/Forward Speech condition, RecipAge predicted approximately the same amount of variance (adjusted $R^2 = 0.136$) as did the three factors in tandem (adjusted $R^2 = 0.282$). But in contrast, TOWRE/SWE predicted no additional variance in this condition. We confirmed with a bootstrap hypothesis test (Efron & Tibshirani, 1998) that TOWRE/SWE did indeed have a differential predictive effect for the two Same Ear conditions ($p < .01$).

Discussion and conclusions

The current study demonstrates the gradual and prolonged developmental profile observed for auditory complex sentence interpretation, particularly in the presence of perceptual and attentional interference. Collapsing across sentence types and competing speech conditions, children up to the age of 11 years differed significantly from adults on mean correct response, a relatively insensitive performance measure. When sentence type and competing speech condition were taken into account, children's performance did not approach adult levels of competency until near-adolescence. Further, general language ability (as assessed with TOWRE/SWE) continued to modulate performance on harder sentence types for older children (over-13s) and adults. The overall pattern of results suggests that the ability to interpret complex language successfully under degraded conditions reflects not only entrenched word order biases but also sensitivity to the frequency of occurrence of particular sentence types (Roland *et al.*, 2006). This is consistent with a gradual, probabilistic account of language development, such as the Competition Model (CM) and other connectionist-style accounts, although at odds with some other positions such as the 'continuity' hypothesis (but see below for further discussion of the limitations of current models such as the CM).

Importantly, the current study indicates that the gradual emergence of syntactic comprehension ability occurs in tandem with, and is intimately related to, the refinement of attentional and perceptual processes. We found that different kinds of informational challenges interacted with the frequency and reliability of language structures over the course of development, producing distinct patterns of performance across age groups. In the absence of competing speech, young children (7–8 years of age) had difficulty interpreting less frequent, more demanding sentence types (i.e. passives and object clefts), which were also particularly vulnerable to the distraction imposed by competing speech in a different ear from the attended signal in these age groups. Further, although 9–10-year-olds showed adult-like performance on difficult sentence types in quiet conditions, competing speech in a different ear still disrupted the interpretation of object cleft sentences in this age group. This suggests that even attentional challenges in the absence of perceptual interference degrade sentence comprehension at certain points in the developmental trajectory.[6]

Older children (11+ years of age) and adults showed no significant effect of different ear competing speech on syntactic comprehension for any of the four sentence types, which may reflect the release from masking associated with the spatial separation of competing speech signals (Cherry, 1953; Drennan *et al.*, 2003; Freyman *et al.*, 2001; Hawley *et al.*, 2004; Litovsky, 2005). This result suggests that the ability to isolate competing speech signals on the basis of spatial information, such that complex syntactic structures may be successfully interpreted, reaches adult-like levels around this point in development, in agreement with Wightman *et al.* (2003).

[5] Estimates of bias-corrected unique adjusted *R*-square values were calculated for each variable using bootstrap sampling (Duda, Hart & Stork, 2001). All reported R^2 values are significantly greater than zero ($p < .05$), as assessed using a data randomization technique.

[6] We should note that the forward speech differs from backward speech not only in semantic content, but in the presence of undistorted phonological information. Thus, interference from forward speech may also derive from increased phonological processing demands – for a related argument regarding the etiology of syntactic deficits in specific language impairments, see Joanisse and Seidenberg, 2003.

In contrast, the increased perceptual and attentional demand imposed by competing speech presented in the *same ear* as the attended signal significantly affected sentence comprehension for all age groups. Young children (7–8 years of age) were most sensitive to the additional perceptual masking effects of same ear competing speech, which significantly reduced accuracy even for sentences with frequently encountered word orders (i.e. actives and subject clefts). In 9–10-year-olds, performance in the same ear competing speech condition was significantly more accurate than in younger children, particularly for actives and subject clefts. The 11–12-year-olds' performance on the more difficult sentence types approached adult levels of accuracy. However, though adult's sentence comprehension was robust to the interference produced by different ear competing speech for all sentence types, same ear competing speech significantly reduced accuracy for object clefts and passives. This finding is consistent with previous studies showing that combined perceptual and attentional stressors selectively disrupt low-frequency, high-cost syntactic structures in normal adults.

Somewhat surprisingly, semantic interference had relatively little if any effect on sentence comprehension, with the possible exception of the unique variance findings discussed below. No semantic interference effect emerged for different ear competing speech, indicating that a competing semantic message does not produce additional interference when the attended and competing signals are spatially separable. Similarly, there was no reliable super-additive effect of semantic demand over and above perceptual interference in what was predicted to be the most challenging listening condition, the same ear, forward speech condition. (Of course, the lack of significant findings could in part be due to ceiling effects or a lack of power despite a large *N*.)

As one would expect for English speakers, for whom word order is a highly frequent and salient syntactic cue and agreement marking is not, agreement effects were relatively small and limited to the hardest sentence type, i.e. object clefts. Nevertheless, the current results are noteworthy for two reasons. First, participants in the more difficult same ear conditions did not show an enhancing effect of agreement cue for any sentence type. This is surprising because, contrary to our expectations, participants do not appear to be using multiple weak cues (i.e. agreement in addition to non-canonical word order) when faced with stressed listening conditions, as has been observed in LI children (Dick *et al.*, 2004). Second, there was no observed age effect for agreement. This result contrasts with the findings of Dick *et al.* (2004), who observed that younger children use agreement cues more than older children.

Conclusions

The transient and non-linear developmental changes observed in the current study are reminiscent of a number of similar trends in the literature on typical and atypical children's language acquisition. For instance, the profile of relative strengths and weaknesses in the language abilities of children with Williams syndrome changes dramatically over developmental time (reviewed in Thomas & Karmiloff-Smith, 2003). The studies of the KE family (e.g. Alcock *et al.*, 2000a, 2000b; Vargha-Khadem, Watkins, Price, Ashburner, Alcock, Connelly, Frackowiak, Friston, Pembrey, Mishkin, Gadian & Passingham, 1998) have demonstrated that a seemingly low-level sensorimotor deficit – like some of our 'stress' conditions – can have quite specific effects on the use of linguistic structures. Research by Bishop and colleagues has suggested that delayed maturation of more general auditory and motor function may be tied to at least some of the linguistic difficulties experienced by children with language impairment (e.g. Bishop, 2002; Bishop & McArthur, 2004, 2005).

More specifically, the developmental increase in the robustness of language processing observed in the present study echoes other recent experimental work on changes in typical children's syntactic abilities, particularly that of Trueswell and colleagues regarding the statistical distribution of different cues in the linguistic environment. Nonetheless, the present study differs from and complements Trueswell *et al.*'s findings in that it implicates a panoply of auditory and attentional skills that support the real-time use of lexical, syntactic and referential cues. Although these auditory skills may seem irrelevant in carefully controlled laboratory conditions, in real life we are constantly assaulted by a sea of interfering noise through which we have to find and segregate relevant speech streams. As such, given the results from the present study, auditory attentional and perceptual skills likely play a very important role in syntactic development, although we hasten to say that the experiment reported here can only shed light on one facet of this broad question.

The present study highlights the fact that existing mechanistic models of language development (such as the CM) need to be updated to incorporate additional constraints. At present the CM, although a useful general account in terms of predicting the importance of cue reliability and the gradual change in sentence comprehension over development, is increasingly showing its age – indeed, it was recently described by one of its authors as 'paleo-connectionist' (Thelen & Bates, 2003). In particular, the CM is agnostic as to the specific effects of semantic, perceptual or attentional interference on language processing, and how these might play out over development. As such, the implications of the current study regarding the interdependence of attention, perception, and higher-level language processing need to be assimilated into a more updated theoretical version (for recent work in this vein see Conway & Christiansen, in press; Farmer, Christiansen & Monaghan, 2006; Joanisse & Seidenberg, 2003; Reali & Christiansen, in press-a, in press-b; Thomas & Redington, 2004).

Such models must also explain how and why the predictive value of individual difference measures (such as TOWRE, age, and speed-of-processing) changes with attentional, perceptual, and semantic load, as revealed by the parcellation of unique variance above. For instance, why do the language skills indexed by the TOWRE only come into play in certain experimental conditions (like SmBk), and not others (SmFd)? Furthermore, why are these cross-condition differences in the predictiveness of the TOWRE only reflected in the parcellation of variance, but not in overall accuracy differences? Previous accounts – including our own (Dick *et al*., 2001, 2003) – would have predicted that with increasing levels of 'cognitive stress', there would be a commensurate increase in the importance of 'language expertise' for successful processing. If TOWRE is in fact indexing such expertise, we must revise our account accordingly. Similarly, we must be able to account for the remarkable degree of individual differences in performance across the lifespan in typically developing individuals (Bates, Bretherton & Snyder, 1988; Nippold *et al.*, 2005), as made explicit by the scatterplots in Figures 6–8.

In conclusion, the results of the present study demonstrate that complex sentence interpretation is dependent upon perceptual and attentional processes throughout the lifespan, and that the nature of this dependence changes over the course of development. Perceptual masking of the speech signal has an early and lasting impact on comprehension, particularly for less frequent sentence structures, whereas increased attentional demand in the absence of masking primarily affects difficult sentence types in younger children. Finally, the predictability of syntactic comprehension abilities by external measures of development and expertise is contingent upon the perceptual, attentional, and semantic milieu in which language processing takes place.

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