LINGUAL ARTICULATION IN CHILDREN WITH DEVELOPMENTAL SPEECH DISORDERS

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Abstract

This thesis presents thirteen research papers published between 1987-97, and a summary and discussion of their contribution to the field of developmental speech disorders. The publications collectively constitute a body of work with two overarching themes. The first is methodological: all the publications report articulatory data relating to tongue movements recorded using the instrumental technique of electropalatography (EPG). The second is the clinical orientation of the research: the EPG data are interpreted throughout for the purpose of informing the theory and practice of speech pathology. The majority of the publications are original, experimental studies of lingual articulation in children with developmental speech disorders. At the same time the publications cover a broad range of theoretical and clinical issues relating to lingual articulation including: articulation in normal speakers, the clinical applications of EPG, data analysis procedures, articulation in second language learners, and the effect of oral surgery on articulation.

The contribution of the publications to the field of developmental speech disorders of unknown origin, also known as phonological impairment or functional articulation disorder, is summarised and discussed. In total, EPG data from fourteen children are reported. The collective results from the publications do not support the cognitive/linguistic explanation of developmental speech disorders. Instead, the EPG findings are marshalled to build the case that specific deficits in speech motor control can account for many of the diverse speech error characteristics identified by perceptual analysis in previous studies.

Some of the children studied had speech motor deficits that were relatively discrete, involving, for example, an apparently isolated difficulty with tongue tip/blade groove formation for sibilant targets. Articulatory difficulties of the 'discrete' or specific type are consistent with traditional views of functional
articulation disorder. EPG studies of tongue control in normal adults provided insights into a different type of speech motor control deficit observed in the speech of many of the children studied. Unlike the children with discrete articulatory difficulties, others produced abnormal EPG patterns for a wide range of lingual targets. These abnormal gestures were characterised by broad, undifferentiated tongue-palate contact, accompanied by variable approach and release phases. These ‘widespread’, undifferentiated gestures are interpreted as constituting a previously undescribed form of speech motor deficit, resulting from a difficulty in controlling the tongue tip/blade system independently of the tongue body. Undifferentiated gestures were found to result in variable percepts depending on the target and the timing of the particular gesture, and may manifest as perceptually acceptable productions, phonological substitutions or phonetic distortions.

It is suggested that discrete and widespread speech motor deficits reflect different stages along a developmental or severity continuum, rather than distinct subgroups with different underlying deficits. The children studied all manifested speech motor control deficits of varying degrees along this continuum. It is argued that it is the unique anatomical properties of the tongue, combined with the high level of spatial and temporal accuracy required for tongue tip/blade and tongue body co-ordination, that put lingual control specifically at risk in young children. The EPG findings question the validity of assumptions made about the presence/absence of speech motor control deficits, when such assumptions are based entirely on non-instrumental assessment procedures.

A novel account of the sequence of acquisition of alveolar stop articulation in children with normal speech development is proposed, based on the EPG data from the children with developmental speech disorders. It is suggested that broad, undifferentiated gestures may occur in young normal children, and that adult-like lingual control develops gradually through the processes of differentiation and integration. Finally, the EPG findings are discussed in relation to two recent theoretical frameworks, that of psycholinguistic models and a dynamic systems approach to speech acquisition.
List of ‘The Published Research’ papers

<table>
<thead>
<tr>
<th>Number</th>
<th>Author(s)</th>
<th>Title and Details</th>
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The above publications are listed in chronological order and referred to collectively in Part 1 of the thesis as *The Published Research*. Specific publications are identified in the text with the relevant superscript number (e.g. publication 1 is referred to throughout as Gibbon and Hardcastle, 1987†). The original publications are presented in full in the same order in Part 2 of the thesis.
Lingual articulation in developmental speech disorders

Research statement

Out of a total of thirty-five publications of which I am an author, I have selected thirteen for the purpose of my PhD submission. I made the selection on the basis that these publications are, in my view, the most significant in their contribution to the field of developmental speech disorders. The publications are the result of research that I carried out, in collaboration with others, over a ten-year period (1987-97), first in the Department of Linguistic Science, University of Reading (1987-92) and then in the Department of Speech and Language Sciences, Queen Margaret College, Edinburgh (1993-present).

Part of the research was supported by externally-funded research grants. Two Medical Research Council grants (G8912970N, 1990-93, and G9117453N, 1993-97) involved the use of instrumental procedures (electropalatography and acoustic analysis) to investigate and treat speech disorders in children. I played a major role in initiating and directing these two research projects, along with co-investigators Bill Hardcastle and Paul Fletcher. One full-time Research Fellow was employed on each of the two projects. The publications that have arisen from these grants have been clinical in orientation and represent a substantial body of work relating to the theoretical investigation and clinical management of children with developmental speech disorders.

Between 1989-92, I was a full-time Research Fellow on an EEC-funded grant (ACCOR, ESPRIT II-BRA framework, 3279). This research concerned articulatory-acoustic correlations in coarticulatory processes in normal speakers, and involved nine centres across Europe. The directors of the ACCOR project were Bill Hardcastle and Alain Marchal. My role in this project was the development of recording methodology, management of subjects, devising new analytic techniques and the preparation of manuscripts for publication. Since 1993, I have been a lecturer in the Department of Speech and Language Sciences at Queen Margaret College, Edinburgh.
Acknowledgements

I owe too many debts to people from Reading University and Queen Margaret College to acknowledge them all individually. Suffice it to say that my research would not have been possible without the collaboration of many individuals. I have a special debt to the co-authors of the thirteen publications submitted in this thesis. Many of my past teachers and colleagues supported my efforts, provided opportunities, and gave timely advice and words of encouragement. In particular I thank Bob Giddings, Jackie Stengelhofen, Pam Grunwell, Penny Hoare, Beryl Kellow, Shula Chiat and Wilf Jones. Colleagues in the Department of Speech and Language Sciences not only extended a warm welcome to me when I arrived in 1993 as a new lecturer, but also unselfishly undertook extra duties in order that I should have time to write my thesis. I have thoroughly enjoyed the many stimulating discussions about the theoretical and clinical implications of the work, and special thanks go to Nigel Hewlett, Jim Scobbie, Jocelynne Watson and Daphne Waters for giving their time so generously.

I am especially indebted to Bill Hardcastle, who has been constant in his friendship, support and enthusiasm over the past twelve years. I have much to thank Bill for – he is a great motivator, and he also encouraged me to become part of the wider research community. I suspect that much of the work would not have come to fruition without his unique combination of optimism and persistence. Thanks also go to Martha Pennington, who has been my advisor over the past year. Discussions with Martha have been most rewarding, and have helped me to place the research work in a broader theoretical context, and her detailed comments on early drafts of the summary hugely improved the finished product.

My partner, Jim, deserves a special vote of thanks, since he has lived with the research work for the past fifteen years. Jim has also patiently provided 24-hour technical support, and has extracted me from computer quagmires on occasions too numerous to mention. Finally I record my thanks to my parents, who have boundless wisdom, generosity and energy. In the knowledge that I will never repay them for everything they have given me, I can only acknowledge the debt, and dedicate this work to them.
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PART 2. The Published Research papers


LINGUAL ARTICULATION IN CHILDREN WITH DEVELOPMENTAL SPEECH DISORDERS

PART 1

Summary and discussion of the contribution of The Published Research to the field of developmental speech disorders
1. Introduction

In a pioneering book published forty years ago entitled ‘The Development and Disorders of Speech in Childhood’, Morley (1957) presented an aetiology-based classification of developmental speech disorders (DSD), along with brief perceptual descriptions of the speech characteristics found in the different groups. One type of speech disorder defined by Morley was dyslalia. Dyslalia was a puzzling condition, since no clear aetiological factors could be identified in children with this type of speech disorder. In the absence of identifiable aetiology, dyslalia was attributed to “persistence of faulty habits of articulation” (Morley, 1957, p. 232). Morley’s work was ground-breaking, and although the terminology for some of the subgroups of DSD has changed over the past forty years, the classification system she proposed is the standard one used today.

Since the publication of Morley’s seminal work, the most significant single influence on the field of speech disorders in children has probably been the application of linguistic frameworks to describe and present clinical speech data. The linguistic influence has had a major impact on views about the nature and the treatment of speech disorders in children. One effect has been that the speech disorder previously known as dyslalia was renamed phonological impairment. Despite advances in descriptions of children’s speech error patterns, the underlying deficit remains elusive and the subject of ongoing controversy. At the centre of the debate is whether the underlying speech disorder reflects cognitive/linguistic difficulties (the currently popular view) or phonetic difficulties in speech perception and/or speech motor control.

A more recent influence on the field of DSD has come from studies originating largely in the 1980s that have used instrumentation for the analysis of speech data. Instrumental studies have much to contribute to our understanding of the underlying nature of DSD and the phonological/phonetic debate, since instrumental procedures are able to measure objectively aspects of speech motor control. One such instrumental technique is electropalatography (EPG). EPG is
one of the few instrumental techniques that is able to record directly the actions of one of the major, but least understood, articulators involved in speech production, namely, the tongue. EPG studies can make an important contribution to the phonological/phonetic debate by providing direct articulatory data, which can be used as compelling evidence for, or against, the presence of speech motor control deficits.

The first studies published in English concerning the clinical applications of EPG appeared in the 1970s, although research into normal speech was already underway at this time. The potential of EPG for providing visual feedback in the remediation of speech disorders was recognised at an early stage, and most of the early publications focused on using EPG in therapy. During the 1980s, clinically oriented studies were published from a few centres around the world (notably Tokyo, Japan; Alabama, USA; and Reading, UK). At this time, publications were mainly concerned with EPG data from those with speech disorders associated with known organic pathology, such as cleft palate and hearing impairment.

The 1990s have seen a rapid expansion in the clinical use of EPG. This has resulted in a steady increase not only in the number of research publications reporting EPG data, but also in the number of clinical centres using the technique (see Nicolaidis, Hardcastle and Gibbon, 1993, for a bibliography of EPG studies). During this time, research has focused increasingly on the contribution that EPG data can make to theoretical issues, such as explanations of speech disorders. EPG data have been especially valuable in the articulatory characterisation of speech disorders, particularly to aspects of production, such as speech motor control, that are not easily captured using standard phonetic notation. Despite the growing interest in EPG and its potential to advance our understanding of different types of speech pathology, articulatory data of the type reported throughout The Published Research remain relatively sparse.
2. Speech disorders in children

Children with speech disorders comprise a large, heterogeneous group. The incidence is uncertain, with estimates varying from 3-10% of the total pre-school/school population exhibiting moderate to severe speech difficulties (Enderby and Philipp, 1986). Various conditions, both biological and environmental, place children at risk for language and speech impairment. These include (with examples given in parentheses): sensory deficits (hearing impairment); cognitive deficits (learning disabilities, mental retardation); psychiatric and emotional disorders (autism); neuromotor disorders (cerebral palsy, Worster-Drought Syndrome); and structural abnormality of the vocal tract (cleft palate, malocclusion, velopharyngeal disproportion).

2.1. Speech disorders of unknown origin

A significant number of children who fail to develop speech in the normal way have no readily identifiable conditions such as those described above. Attempts over the past four decades to characterise the nature of idiopathic speech disorders in children have produced divergent accounts. Morley's (1957) view that idiopathic disorders were phonetic in nature, due specifically to faulty motor learning of articulatory gestures that at a later stage became habitual, persisted throughout the 1960s and 1970s (see McReynolds, 1988, for a summary). Speech sound errors produced by children were identified and remediated as though they were separate, unrelated phenomena. At this time, the term functional articulation disorder replaced Morley's (1957) term dyslalia, with 'functional' indicating that the disorder was not associated with organic pathology, and 'articulation' indicating the assumed motoric origin of the speech difficulty.

Recent accounts, however, view speech disorders of unknown aetiology quite differently. Instead of a phonetic disorder, the origin of DSD is now thought to be cognitive/linguistic. This view has come about largely through the influence of early work by a number of linguists (most notably Jakobson, 1968; Smith, 1973; Stampe, 1969) who introduced linguistic descriptions of child speech
patterns. Linguistic descriptions in the form of phonological analyses were later used to characterise clinical speech data (e.g. Compton, 1970; Ingram, 1976; Grunwell, 1981; and see Leonard (1995) for a recent review).

Phonological analyses of clinical data from children with DSD have revealed that speech error patterns are often highly complex and idiosyncratic, involving:

- a reduced system of phonological contrasts
- a restricted phonetic inventory
- limited word and syllable shapes
- persisting speech error patterns
- unusual error types
- extensive variability

(See Gibbon and Grunwell, 1990, for a review and explanation of the above). Importantly, phonological analyses were able to show that speech errors produced by children were not separate, unrelated entities. Instead, linguistic descriptions revealed the systematic, rule-governed nature of speech errors in children, and terminology from the field of phonology was adopted in order to capture these regularities.

The shift of emphasis from articulation to phonology was reflected in a change in the diagnostic classification used for speech disorders of unknown origin, with phonological impairment (synonymous with phonological disorder and phonological disability) becoming the preferred term. The label phonological impairment varies in scope, with Stackhouse (1993) suggesting that it should be used in a purely descriptive sense to refer to all speech output difficulties that involve a neutralisation or loss of phonological contrasts, regardless of the underlying cause. However, phonological impairment is much more commonly used as a diagnostic label where the underlying origin of the disorder is considered to be abnormal speech sound organisation. Grunwell summarises this latter position, stating that:

phonological disorders ... because they occur in the absence of any known physical or physiological deficits, must result from breakdowns
at the cognitive level of linguistic knowledge and organisation. (Grunwell, 1990, p. 5.)

Thus, the widespread use of phonological descriptions of clinical speech data has generated a radical change in views about the underlying deficit in DSD of unknown origin.

2.1.1. Evidence for cognitive/linguistic difficulties

Evidence to justify the paradigm shift described above and to support the reality of the cognitive/linguistic account of DSD comes from a variety of sources. The following numbered sections offer examples of the types of evidence commonly cited by researchers such as, for example, Grunwell (1981), Leonard (1995), and Stoel-Gammon and Dunn (1985).

1. In speech samples from children, there is often evidence of variability of articulatory production, suggesting that children can produce sounds or sound classes, but that they do not always use them according to the sound system of the language being acquired. Leonard (1995) gives an example (i) from a child described as having a phonological impairment:

   (i) lion → [la] light → [da]

   (ii) puddle → [pAg~l] puzzle → [pAd~l]

   The evidence in example (i) suggests that articulatory difficulties cannot account for the use of /d/ in light, since the /l/ is produced normally in lion. Smith’s (1973) famous puzzle phenomenon is shown in (ii). Here, the child (Smith’s son Amahl, who had normal speech development) appears unable to produce /d/ in puddle, but is able to produce /d/ as a realisation of another target (in this case, /z/). Smith states that articulatory difficulties alone are insufficient to account for such puzzles, which have been noted to occur extensively in the speech of both normally developing and phonologically impaired children.

2. Speech error patterns produced by children tend to be systematic and rule-governed, suggesting that the difficulty is learning the phonological rules of the target language (Dodd, 1995; Grunwell, 1981).
3. Distorted productions of sounds, i.e. phonetic errors, are comparatively rare in the speech of children with phonological impairment. Shriberg and Kwiatkowski (1988) found that omission and substitution errors greatly outnumber errors of distortion in the speech of these children. Leonard states that:

if speech sound difficulties were due principally to errors of articulatory accuracy, distortions (which appear to be near misses of the articulatory target) should represent a much higher percentage of the errors observed. (Leonard, 1995, p. 575.)

4. While studies have shown that DSD may be associated with various causative factors (see Shriberg, Kwiatkowski, Best, Hengst and Terselic-Weber, 1986), and there is some evidence for below-age-level phonetic (perceptual and motor) skills (e.g. Catts and Jensen, 1983; Waters, 1992; Watson, 1997), there is a lack of conclusive evidence that any of these factors can account for DSD.

2.1.2. Interpretation of children’s speech errors

In many of the perceptually-based studies cited thus far, the distinction between phonological and phonetic errors is of paramount importance in the diagnosis and the explanation of DSD. In making this distinction, studies typically rely on data from standard transcriptions. The symbol selected by the transcriber carries implicit assumptions about whether a child has (i) produced a sound accurately (e.g. /k/ in car → [k]); (ii) produced a phonological substitution (e.g. /k/ in car → [t]); (iii) omitted a sound (e.g. /k/ in car → φ); or (iv) produced a non-English sound, in other words a phonetic distortion (e.g. /k/ in car → χ).

Speech errors of substitution and omission are commonly interpreted as phonological errors, whereas distortions are considered phonetic errors (see Berenthal and Bankson, 1988; Dodd, 1995; Grunwell, 1990). Phonological errors are further interpreted by many as reflecting high-level cognitive/linguistic deficits, whereas phonetic errors are generally considered as reflecting lower level, speech motor control difficulties (Berenthal and Bankson, 1988; Bradford and Dodd, 1996; Dodd, 1995; Grunwell, 1990; Leonard, 1995). Shriberg and Kwiatkowski (1988) state that since the majority of children with phonological
impairment show predominantly phonological errors, they are accurately judged as having cognitive/linguistic impairment. A much smaller group is considered to have primarily phonetic errors, and children with this type of speech disorder are usually referred to as having articulation disorders (Dodd, 1993; 1995; Grunwell, 1981). Children that Dodd (1995) refers to as having articulation disorders are described as having difficulties with the production of specific classes of speech sounds, usually sibilant and/or liquid targets.

2.2. Limitations of transcription data

Standard auditory-impressionistic transcription is the most frequently used method for investigating both normal and disordered child phonology for both research and clinical purposes. Grunwell (1993) recently stated that “auditory-articulatory descriptions remain the lingua franca of the speech and language therapy profession” (p. 2). Reasons for the popularity of transcription are clear: it records functionally relevant aspects of production; it is an easily accessible dimension of speech; it requires no complex instrumentation; and there is an extensive literature based on this methodology.

Although it is widely used, there are well-recognised problems associated with using transcription data alone for investigating disordered speech generally, and in particular for the purpose of measuring speech motor control (Butcher, 1989; Hardcastle, Morgan Barry and Clark, 1987). One limitation is that the activity of transcription affords at best an indirect representation of the actions of the articulators such as the tongue, with the result that articulatory information must be inferred by the transcriber from an accumulation of complex cues contained in the acoustic signal.

An even greater issue for transcription-based analyses is the accumulating evidence from acoustic studies showing the existence of covert contrasts in children’s speech. The term covert contrast was coined by Hewlett (1988) to describe instrumentally measurable differences between target phonemes that are neutralised in listeners’ perceptions. In other words, it can be demonstrated by careful instrumental analysis that some children who appear even to a trained
listener to neutralise contrasts in reality produce consistent articulatory differences between target phonological categories. The phenomenon of covert contrast was identified in the speech of normally developing and phonologically impaired children in the early 1980s, and had been referred to previously as partial neutralisation, sub-perceptual contrast or sub-phonemic contrast. (For further discussion of the theoretical and the clinical implications of covert contrasts, see Sections 4.3, 5.4, 6.2.1 and references therein.)

A final limitation of transcription is that it is not a suitable methodology for measuring speech motor skill, which is defined by Fletcher (1992) as “spatial and temporal proficiency in executing a motor task” (p. 1). Fletcher (1992) views speed, spatial (i.e. positional) accuracy, consistency of articulatory movement and movement efficiency as hallmarks of motor skill development, none of which can be measured accurately using a linear notation system (Oller and Eilers, 1975).

2.3. The importance of instrumental articulatory data

Children with DSD comprise a heterogeneous group that presents with diverse and complex speech characteristics. The currently popular view is that the origin of this type of speech disorder is cognitive/linguistic, not articulatory/motoric, a view which is grounded on evidence from studies that have used standard transcriptions of children’s speech error patterns. However, studies of covert contrasts illustrate that the psychological phenomenon of categorical perception, which is unavoidable when transcribing clinical speech data, biases listeners to make judgements that favour ‘phonological’ errors of substitution and omission over ‘phonetic’ errors of distortion. It is possible that the cognitive/linguistic explanation has emerged as a result of a methodological artefact, rather than a true reflection of the origins of DSD.

Although a number of studies have used acoustic analysis to investigate speech motor skills in children with DSD (e.g. Catts and Jensen, 1983; Waters, 1992; Weismer and Elbert, 1982), few studies have reported direct articulatory data. The Published Research makes a major contribution to the field of DSD in reporting articulatory (EPG) data from a group of children with speech disorders.
of unknown origin, data that are subsequently interpreted in order to inform the phonological/phonetic debate. If the speech errors found in children with DSD reflect cognitive/linguistic difficulties, then articulatory data would be expected to support, and be consistent with, the findings of previous studies that have used transcription data. Articulation, as revealed by EPG, would be expected to show: predominantly substitutions/omissions; relatively few instances of distorted articulatory configurations ("near misses" as Leonard, 1995, describes them); and developmentally normal speech motor skills. The extent to which the articulatory (EPG) data from children with speech disorders support these expectations is discussed in Sections 4 and 5.

Prior to these discussions, and as a necessary point of departure, Section 3 provides background information concerning the EPG technique and tongue movement control in normal speakers. In addition, the results of a series of EPG studies concerning lingual coarticulation in normal speakers are summarised in the next section, as these findings were to lead to important insights into the speech motor control abilities in the children with DSD investigated in The Published Research.

3. **EPG description of lingual articulation**

The tongue is one of the largest and most important speech organs, being actively involved in the production of the majority of consonants and vowels. The tongue’s movements within the vocal tract are characterised by speed and flexibility. For example, it is able to adopt a range of postures and motions, including: arching back the tip/blade for retroflex sounds (e.g. the usual realisation of English /r/); grooving the tip/blade for sibilant sounds (e.g. /s/); arching the posterior tongue for velarised [h]; and sliding forward (looping) the tongue body during velars (e.g. /k/). Tongue movements vary in speed and velocity, from the rapid accelerations and decelerations characteristic of ‘ballistic’ stops, to smoother ‘ramp’ gestures characteristic of vowels. In the production of natural, intelligible speech, tongue movements are not only fast and complex, they are characterised by precision,
consistency and a high degree of co-ordination with the movements of other speech organs, i.e. the respiratory system, laryngeal structures, velum, jaw and lips.

The tongue plays a key role in speech production, but its behaviour is notoriously difficult to record (for recent reviews see Stone, 1997; Hardcastle, 1996). The problem of finding a suitable methodology for recording the actions of the tongue is due to its visually inaccessible location within the oral cavity, and the speed and complexity of its movements. Since many instrumental techniques used for measuring tongue activity involve specialist experimental procedures, and are often invasive to some extent, finding a suitable methodology for use with young children is an even greater problem. EPG is an instrumental technique that objectively measures one phonetically important aspect of tongue movement, that is, its contact with the hard palate. (For an overview of the Reading EPG techniques, see Hardcastle, Gibbon and Jones, 1991; for a more recent summary of the main features of the Reading EPG3 system, see Hardcastle and Gibbon, 1997). An important advantage of EPG is that it is one of the few instrumental techniques suitable for investigating tongue activity in young children.

3.1. Description of Reading EPG

Over the past ten years, the Reading EPG has undergone major developments, incorporating new technologies as they have become available, in order to maximise the technique's user-friendliness for research and clinical purposes. Various versions of the Reading EPG have been used throughout The Published Research, and the specifications of these different experimental procedures are described in the relevant methodology sections of the publications contained in The Published Research. The main differences between earlier and later versions of EPG are the sampling rate used, the data processing facilities available and the different systems' ability to record EPG data simultaneously with other channels (e.g. oral and nasal airflow, Laryngograph, Electromagnetic Articulography, etc.).
3.1.1. The artificial EPG palate

An essential component of EPG is a custom-made artificial palate, the design and the manufacture of which has not changed over the ten-year period of The Published Research. The artificial palate is moulded to fit as unobtrusively as possible against a speaker's hard palate. Embedded in it are 62 electrodes exposed to the lingual surface. When contact occurs between the tongue surface and any of the electrodes, a continuously varying signal is conducted to an external processing unit. EPG registers characteristic spatial patterns for lingual obstruents such as (in English) /t/, /k/, /s/, /ʃ/, /tʃ/ (and their voiced phonological cognates), the palatal approximant /j/, lateral /l/ and nasals /n/, /n/. The relatively close vowels /ə/, /u/, /e/ and diphthongs with close off-glides such as /eɪ/, /aɪ/ and /ɔɪ/ also show measurable degrees of tongue-palate contact in EPG recordings.

3.1.2. EPG raw data

EPG raw data are displayed as sequences of two-dimensional schematic representations, referred to as palatograms or EPG frames. EPG raw data in this form reveal phonetically relevant articulatory features, such as the location of tongue-palate contact (spatial information), dynamic information about the timing of tongue movement (temporal information), and details of lingual coarticulation. EPG data thus provide a direct, detailed and objective record of these aspects of tongue behaviour from one perspective, namely, its movements against the hard palate.

3.1.3. Limitations of EPG

There are important aspects of tongue movement that EPG does not record. For example, it is not possible to know from EPG data alone which part of the tongue is making contact with the palate, nor is it possible to know the distance of the tongue from the hard palate. Also, since EPG only records contact against the hard palate, actions of the tongue that occur at a location anterior to the hard palate (e.g. bilabial and dental articulations) or at a more posterior place (e.g. uvular, pharyngeal and glottal articulations) are not detected using EPG. These limitations are overcome to a large extent in the new speech production analysis facility at
Lingual articulation in developmental speech disorders, Part 1

Queen Margaret College, Edinburgh, in which EPG data can be obtained simultaneously with data recorded from an Electromagnetic Articulograph (EMA: see Section 3.4 for further details).

Another limitation of EPG is the schematic nature of the palatograms, which do not account for the wide range of different sizes and shapes of speakers' hard palates, nor the relationship between the maxilla and the mandible. This information is particularly important when interpreting the EPG patterns from subjects with small or misshapen hard palates or malocclusion (e.g. young children and those with alveolar clefts). However, interpretation is aided by well-defined criteria used for electrode placement (see Hardcastle, Gibbon and Jones, 1991\textsuperscript{5}), which provide a basis for comparison between different speakers.

3.1.4. Data reduction

Raw EPG data can be unwieldy due to the number of palatograms produced (100 or 200 EPG frames per second depending on the sampling rate selected), and so a need arises for data reduction methods and quantification of contact patterns for statistical purposes. When devising suitable data reduction procedures, it is important that processing will give results that reflect phonetically relevant parameters and are not simply artefacts of the analysis procedure itself. Hardcastle, Gibbon and Nicolaidis (1991\textsuperscript{6}) review EPG data reduction methods of three major types: (i) those that capture spatial details about the location of tongue-palate contact; (ii) those based on dynamic changes in lingual activity; and (iii) indices that have been used to reduce the EPG contact information to a single value, giving an overall characterisation of contact patterns. The methods described in Hardcastle, Gibbon and Nicolaidis (1991\textsuperscript{6}) have been developed and used extensively throughout The Published Research in order to capture details such as place of articulation, tongue dynamics and coarticulation.

3.2. Place of articulation

Theories of phonetics have nearly always involved some notion of place of articulation (Ladefoged and Maddieson, 1996), since it identifies the location
within the oral cavity at which major articulatory events occur. Of the five major active articulators that Ladefoged and Maddieson (1996) distinguish, two are relevant here, since their activities can be detected using EPG. The two articulators are the tongue tip/blade and the tongue body. The tongue body can be further divided into front and back regions, the front part being that part which rests below the hard palate, and the back that part which can be located (when at rest) below the velum. Although place of articulation retains a pre-eminent status in phonetic description, this is probably because early phonetic studies were based on X-rays, which record midsagittal data. Fletcher (1992) emphasises the importance of contact between the lateral borders of the tongue and the hard palate, especially for production of lingual stops, lingual fricatives and high vowels. EPG is one of the few techniques that records the activity of the lateral margins of the tongue as they contact the borders of the hard palate.

EPG records the movements of the tongue tip/blade and the front of the tongue body as they make contact with the passive articulator, the hard palate. Ladefoged and Maddieson (1996) identify four phonetically relevant regions of the hard palate — alveolar, post-alveolar, palatal and velar. These regions have been correlated to zones on the EPG palate (see Gibbon, Dent, and Hardcastle, 1993; Recasens, 1990). As pointed out earlier, one of the limitations of EPG is that it does not record which part of the tongue is contacting the palate. However, it is possible to make inferences about this: where EPG contact occurs in the anterior (i.e. alveolar and post-alveolar) region of the palate, it is inferred that the articulation involves the tongue tip/blade; and where contact is in the posterior (i.e. palatal and velar) region, it is inferred that the articulation involves the tongue body.

3.3. Tongue movement control

The tongue is a soft, flexible organ that does not have its own internal bony or cartilaginous skeleton (Dubrul, 1977; Kier and Smith, 1985), but instead has a hydrostatic skeleton. Kent (1992) captures the unusual properties of the tongue as
a fluid-filled balloon by referring to it as a *muscular hydrostat*, observing that the tongue:

forms its own skeleton to support movement and then performs movements and shape changes relative to that skeleton .... They [muscular hydrostats] are incompressible at physiological pressures and therefore can change in any one dimension only by making compensatory changes in another dimension. (Kent, 1992, pp. 71-72.)

Smith and Kier (1989) state that bending a hydrostat (e.g. for /l/ or /r/ production) involves two simultaneous adjustments, namely a decrease in length accompanied by resistance to change in diameter. If diameter changes in the tongue are not resisted, it will shorten but not bend (Kent, 1992). In other words, as the tongue moves, it also deforms, presenting the speaker with some unique difficulties in terms of motor control. Such difficulties are compounded by the fact that in terms of articulatory control, the tongue functions as two independently controllable articulators (Hardcastle, 1976). Independent control implies that: (i) tongue tip/blade movement can occur relatively independently of tongue body movement (as occurs, for example, in the production of an alveolar stop in an /i/ environment); (ii) tongue body movement can occur relatively independently of tongue tip/blade movement (as occurs, for example, in the production of velarised laterals); and (iii) the movement of the two articulators can combine and overlap in time, in other words, coarticulate.

Figure 1 illustrates the third property, i.e. that of tongue tip/blade and tongue body coarticulation during a normal speaker’s production of the /kl/ sequence in a clock. From this figure, it can be seen that velar closure for /k/ extends from frames 51-60, and alveolar closure for the lateral /l/ from frames 59-67. Tongue movement in anticipation of /l/ production occurs well before velar closure is released (EPG lateral contact starts to build up in frame 56) and there follows a brief period (frames 59-60, equivalent to 20 ms) of complete velar/alveolar articulatory overlap.
3.4. Tongue tip/blade and tongue body coarticulation

Interest in tongue tip/blade and tongue body coarticulation in normal speakers led to a series of studies within the ACCOR project (1989-92), which investigated the relative influence of biomechanical versus linguistic influences on the production of /kl/ clusters of the type illustrated in Figure 1. Spatial and temporal control of tongue tip/blade and tongue body movements in six European languages was investigated in a study by Gibbon, Hardcastle and Nicolaidis (1993). One of the major findings, and one which occurred in all of the languages investigated, was of a more posterior placement of the tongue body for velars in /kl/ clusters than in singleton /k/. Gibbon, Hardcastle and Nicolaidis (1993) postulated that biomechanical properties of the tongue could affect articulatory placement for /k/. For example, Sproat and Fujimura (1993) suggest that tongue blade narrowing for /l/ is accompanied by an increase in tongue blade length, and this may cause a degree of dorsal retraction. If this is true, it is possible that velar gestures in /kl/ sequences are retracted due to the presence of an upcoming /l/.

Possible explanations for velar retraction in /kl/ clusters were explored in a follow-up study by Hardcastle, Vaxelaire, Gibbon, Hoole and Nguyen (1996), which used simultaneously recorded EPG and Electromagnetic Articulography (EMA) data. EMA data are highly complementary to EPG, since EMA tracks the movement of miniature coils attached to the tongue’s surface, and provides details of tongue surface shape and proximity to the hard palate in the midsagittal plane. The EMA traces in the Hardcastle et al. (1996) study revealed that forward
moving ‘looping’ trajectories (previously described from X-ray data by Perkell, 1969) occurred during production of singleton /k/ (e.g. in cap). However, the loops were blocked in the /kl/ cluster (e.g. in clap). More precisely, in the /kl/ cluster, the first portion of the loop occurred, but the forward movement of the tongue body was suddenly and dramatically halted at the exact moment when the tongue tip began its ascent upwards for the lateral. In other words, it was not so much that tongue body placement was retracted (although this was how it was recorded on EPG records), but rather that the tongue body did not loop forward to the same degree in the context of the upcoming lateral. It may be that biomechanical properties of the tongue (such as those associated with muscular hydrostats) mean that tongue tip/blade raising directly obstructs tongue body looping, as Gibbon, Hardcastle and Nicolaidis (1993\textsuperscript{8}) suggest. However, there are alternative explanations, such as the possibility that velar loops are blocked due to jaw raising for the lateral. Experiments are currently underway in the Speech Research Laboratory at Queen Margaret College to test these different hypotheses.

The knowledge of lingual dynamics in /kl/ clusters obtained from these studies has stimulated related studies of both normal speakers (e.g. Nguyen, Marchal and Content, 1996, who investigated /kl/ clusters in French) and pathological speakers (e.g. Wood, 1997). Wood (1997) extended the work on /kl/ clusters described above by adopting a similar methodology to that of Gibbon, Hardcastle and Nicolaidis (1993\textsuperscript{8}) to examine the timing of /kl/ clusters in adults with acquired neurogenic speech disorders. Figure 2 (adapted from Wood, 1997) shows the timing relationships between the tongue body and the tongue tip/blade in the /kl/ sequence in a clock over ten repetitions (labelled R1-R10) by one normal and one adult dyspraxic speaker.
Figure 2. Timing of velar and alveolar gestures in /kl/ sequences

(a) Timing of ten repetitions of /k/ and /l/ gestures in the /kl/ sequence in a clock produced by a normal speaker

(b) Timing of ten repetitions of /k/ and /l/ gestures in the /kl/ sequence in a clock produced by a dyspraxic speaker
The upper graph in Figure 2 shows the data for the normal speaker, whose repetitions are executed in all instances in less than 140 ms. In addition, the EPG patterns from the normal speaker reveal articulatory overlap between the \(/k/\) and \(/l/\) gestures (Figure 1 in the previous section presents the EPG patterns corresponding to the normal speaker’s R7 production as shown in Figure 2a).

Figure 2b presents results from the dyspraxic speaker. Although velar and alveolar gestures were produced by the dyspraxic speaker, and in the correct sequence, both \(/k/\) and \(/l/\) are abnormal since (i) they are produced with longer durations (nearly twice as long as the normal speaker), and (ii) there is no evidence of articulatory overlap, suggesting that coarticulation is disrupted in this speaker. Importantly, the \(/kl/\) clusters produced by the dyspraxic speaker were judged to be normal from an auditory-impressionistic transcription. Further research is needed to investigate the causes of disrupted lingual coarticulation in speakers with acquired dyspraxia. It may be that it is the precise timing relationships between tongue tip/blade and tongue body gestures, or their spatial relationships – or perhaps the need to control both aspects of production simultaneously – that causes temporal co-ordination to break down.

The discussions so far have been concerned with evidence supporting the notion that the tongue tip/blade and the tongue body are two separately controllable articulators in normal speakers. The ability of these two articulators to function relatively independently and to coarticulate in the ways described in the Gibbon, Hardcastle and Nicolaidis (1993) study provided important insights into speech motor control deficits in children with DSD.

4. Characteristics of lingual articulation in DSD

Articulatory data from fourteen children with DSD of unknown aetiology are presented in The Published Research: one child in Gibbon and Hardcastle (1987); two children in Gibbon (1990); one child in Gibbon, Dent and Hardcastle (1993); and ten children in Gibbon, Hardcastle and Dent (1995). From perceptually-based analyses, the children comprised a heterogeneous group in
terms of their phonological and phonetic speech errors, and in terms of the variability of their error patterns.

This section summarises the findings from The Published Research, in order to (i) highlight the major characteristics of lingual articulation in the children studied and (ii) show the relationships between the abnormal EPG patterns and perceptually-based analyses. Examples of EPG data have been selected to illustrate typical articulatory characteristics of individual children, and further examples can be found in the original articles. Due to the ongoing controversy about terminology, as outlined in Section 2, the term developmental speech disorder (DSD) will be adopted to refer to the heterogeneous group of children investigated in The Published Research, all of whom presented with speech disorders of unknown origin.

4.1. Annotation points

Throughout The Published Research, EPG data have been subjected to various data reduction techniques, as described in Section 3.1.4. In the sections that follow, in order to provide consistency throughout, full printouts of EPG palatograms are shown. For stops, three standard annotation points are identified on the full printouts: (i) start of closure – the frame preceding the first palatogram showing complete midsagittal contact across the palate (this point represents the end of the approach phase of the stop and the beginning of the stop closure phase); (ii) maximum contact – the frame with the highest number of contacted electrodes during the closure phase, or where there is a sequence of such frames, then the frame located in the centre of the sequence is selected (this is the point of maximum articulatory constriction); and (iii) release – the first frame where contact is broken (this point is the end of stop closure and the beginning of the release phase of the stop). These annotation points are illustrated in Figure 3, which shows a full EPG printout of the word-initial /t/ in tar, recorded from a normally developing child (N1, aged 12;03, from Gibbon et al., 1995⁹).
4.2. EPG error classification

Hardcastle and Gibbon (1997) devised a qualitative EPG error scheme in which tongue-palate contact patterns can be classified as: (i) spatial errors, (ii) temporal errors, (iii) serial ordering abnormalities or (iv) errors of substitution and omission. Examples of an EPG spatial distortion and an EPG substitution error are given in Sections 4.2.1 and 4.2.2 below (and see Hardcastle and Gibbon, 1997, for further examples). Judgements about the abnormality of EPG patterns are based on available normative data together with considerable experience in analysing EPG data. Studies that report normal adult EPG patterns are summarised in Hardcastle and Gibbon (1997), Hardcastle, Gibbon and Jones (1991) and Nicolaidis et al. (1993). Normative data for children aged 7-12 years are reported in Gibbon et al. (1995) and Hardcastle and Morgan (1982).

Figure 3. Alveolar stop produced by a normal child, /t/ → [t]

4.2.1. EPG spatial distortions

Spatial distortions differ from normal EPG patterns in terms of the type of tongue-palate contact configuration that occurs (see Hardcastle and Gibbon, 1997, for further details). EPG spatial distortions come in various forms: (i) asymmetric, skewed configurations for /s/ produced by adults with acquired neurogenic disorders (Hardcastle and Edwards, 1992); (ii) excessive palatal contact for /s/ in children with DSD (Gibbon and Hardcastle, 1987); (iii) incomplete lateral
contact for /s/ seen in DSD (Gibbon et al., 1995); and (iv) excessive contact across the whole of the palate (Gibbon, 1990; Gibbon et al., 1995).

An example of an EPG spatial distortion is given in Figure 4, which shows an EPG printout of word-final /d/ in shed, transcribed as a normal production (D8, aged 8;06 years, from Gibbon et al., 1995). Compared to the normal child’s production of an alveolar stop (see Figure 3), D8’s EPG patterns show broad, undifferentiated tongue contact across the palate. The result at maximum contact (frame 248) is complete contact between the tongue and the hard palate, other than in the most anterior region of the palate. This broad, undifferentiated EPG configuration suggests not only an abnormally high tongue body position but also an abnormally convex tongue body surface shape for an alveolar target (Fletcher, 1992). The EPG patterns in Figure 4 are quite different from the discrete lateral and alveolar contact that forms the ‘horseshoe-shape’ so characteristic of normal alveolar stops (see Figure 3). In the example shown in Figure 4, it is argued that since transcription identified a normal production and the EPG data an articulatory abnormality, the information from the two sources (transcription and EPG) is divergent in this case.

Figure 4. An EPG spatial distortion, /d/ → [d]
4.2.2. EPG substitutions

EPG substitutions are judged to be normal in terms of their spatial configuration, but are considered errors because of their abnormal location in a particular phonetic context or in a particular lexical item. For example, a normal EPG alveolar stop pattern produced at the beginning of car (normally produced with a velar stop pattern) would be considered an EPG substitution. EPG substitutions are articulatory errors that would be expected to arise as a result of simplifying phonological processes (e.g. gliding of liquids, velar fronting, fricative stopping, etc.). A further expectation is that where phonological contrasts are heard as neutralised – as frequently occurs in the speech of children with DSD – the EPG patterns for the resulting homophones will be indistinguishable. For example, if a child is heard to say car as [tɔʊ] and tar as [tɔː], the prediction is that the EPG patterns for homophonous /t/ in the two words will be the same. Figure 5 shows the only example of an EPG substitution recorded in The Published Research.

Figure 5. MB's production of shoe and you, heard as homonymous [jɪː]

(a) MB's production of /ʃ/ in shoe, /ʃ/ → [ʃ]

(b) MB's production of /j/ in you, /j/ → [ʃ]

The data in Figure 5 were recorded from MB (aged 4;10 years, from Gibbon, 1990\(^3\)), whose speech contained many examples of phonological substitutions.
One process involved gliding of fricatives and liquids in word-initial position (i.e. /s, z, ʃ, ʃ, j, j' → [j]), which resulted in extensive homophony and neutralisation of phonological contrasts (e.g. Sue, zoo, shoe, Lou, and you were all judged by listeners to be produced by MB as [juː]).

The EPG data for /ʃ/ in shoe are shown in Figure 5a, and those for /j/ in you in Figure 5b. The EPG patterns for /ʃ/ → [ʃ] are the same in terms of their spatial configurations as the EPG patterns for /j/ → [j], though in both cases showing asymmetrical EPG patterns with increased contact in a 'wedge-shape' configuration on the left side of the palate. In this example, the EPG data and the transcription data converge in so far as the tongue-palate contact is consistent with the perceptual analysis. This agreement holds regardless of the idiosyncratic EPG patterns and in spite of an apparent difference in the duration of the two gestures, with the fricative being longer than the liquid target in this example.

4.3. Perceptual neutralisations

EPG substitutions of the sort illustrated in Section 4.2.2 have been rarely reported in The Published Research. More commonly found were articulatory covert contrasts, i.e. different EPG patterns for target contrasts that were heard as homophonous. The articulatory data to be described in the next section are especially significant, since they represent the only direct articulatory evidence of covert contrasts reported in the literature.

In Gibbon (1990³), EPG data from two children are described. One of the children, MB, was systematically using a number of phonological processes, including alveolar backing (another of her processes, that of gliding, is described above in Section 4.2.2). The effect of alveolar backing was that listeners heard many phonological substitutions in MB's speech, e.g. duck → [gAk], daddy → [gægi] and so on. EPG printouts of an alveolar target from MB are shown in Figure 6a and of a velar target in Figure 6b (from Gibbon, 1990³). Although even phonetically-trained listeners heard the alveolar/velar contrast as neutralised, the EPG data in Figure 6 reveal that tongue-palate contact patterns for alveolar targets were always completely different from those of velar targets. In other words, at the
articulatory level the alveolar/velar contrast was not neutralised at all, although at
the perceptual level this is how listeners judged it.

Figure 6. EPG printout of a perceived neutralisation

(a) Alveolar target, heard as a substitution, /d/ → [g]

(b) Velar target, heard as a normal production, /g/ → [g]

MB’s productions of alveolar targets (Figure 6a) are different from a normal
child’s at the three main stages of stop production as identified from the
annotation points (see Section 4.1 and Figure 3). MB has abnormal velar contact
at the start of closure, followed by tongue contact that moved forward into the
alveolar region. Velar contact is maintained during stop closure, resulting in a
period of double velar-alveolar closure. Alveolar contact then decreases during the
closure phase, and the stop is released in the velar region. The location of the start
of closure and release phases of MB’s alveolar targets in the velar region of the
palate would have contributed to perceptual cues that led listeners to judge these
gestures as velar substitutions. The EPG contact that moved into the alveolar
region took place during the silent closure phase of the stop, and would not have
been detected easily by the human ear. However, if the position of the tongue
tip/blade were higher in the vocal tract for alveolar targets than for velars (as is
suggested by the EPG data in Figure 6), then the covert contrast captured so
clearly in the EPG patterns would probably have been detected in an acoustic analysis.

An articulatory covert contrast of a somewhat different type was produced by D8 (aged 8;06 years, from Gibbon et al., 1995). D8 had perceptually distorted productions of /s/ and /ʃ/ targets, which were heard as homophonous, lateralised fricatives [ʃ]. Predictably, all /s/ and /ʃ/ targets were produced as EPG spatial distortions. However, the EPG data unexpectedly revealed that D8 produced all /ʃ/ targets with a more retracted place of articulation than /s/ targets, as would occur in a normal speaker’s production of these targets. This finding suggests that D8 had some relevant articulatory knowledge about this perceptually neutralised phonological contrast. The general finding illustrated by these examples is that articulatory data and perceptual judgements are not congruent in all cases. In some instances, perceptual neutralisations are not accompanied by identical EPG patterns, as the case of covert contrast illustrates.

4.4. Perceptual variability

There is ample evidence in the literature of variability in the speech of children with DSD (Dodd, 1995; Grunwell, 1981; Leonard, 1995). Kent (1992) proposes that variability in phonological organisation should be distinguished from variability in motor performance (i.e. phonetic variability), and goes on to suggest that “motor variability can be so great as to result in an apparent variability in [phonological] organization” (Kent, 1992, p. 80). The following examples illustrate how the EPG data described in The Published Research have highlighted articulatory phenomena that can in some cases give rise to perceptually variable speech errors.

4.4.1. Articulatory variability following a period of speech therapy

MB was consistent in her use of the phonological process of alveolar backing at the time of the initial recording (reported in Gibbon, 1990). Some months later, following a period of speech therapy, MB was heard to produce alveolar targets variably, so that on some occasions and in some words they were heard as normal
alveolars, and on other occasions they were heard as velar substitutions. Two examples of EPG data recorded during this period of variability are shown in Figure 7.

Figure 7. MB's variable productions of alveolar targets
(a) Target /d/ in dart, heard as a substitution, /d'→[g]

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(b) Target /d/ in deer, heard as a normal production, /d'→[d]

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The example shown in Figure 7a was judged by listeners to be a phonological substitution, whereas Figure 7b was judged as a normal production. From the EPG patterns, the two gestures are similar in terms of their start of closure and maximum contact frames. The main difference is located in the release phase of the stops. In Figure 7a the stop is released in the velar region and in Figure 7b the stop is released in the alveolar region. The different locations (velar and alveolar respectively) of the release phases of the two stops probably account for the perceptual variability in this case. Importantly, the EPG patterns in Figure 7a did not resemble those of a normal velar stop, nor did the patterns in Figure 7b resemble a normal alveolar stop. Thus, analysis of the EPG data was able to
document in detail the subtle articulatory changes that occurred in stop production as therapy progressed, and at the same time revealed the articulatory basis of the apparent phonological errors in her speech.

MB, like D8 and many of the other children described in The Published Research, produced broad, undifferentiated EPG contact patterns for a wide range of targets. One characteristic of stops and fricatives produced with broad gestures is that during the phase of maximum constriction, tongue-palate contact in the anterior region of the palate is always accompanied by simultaneous posterior contact (this type of EPG pattern is interpreted further in Section 5.2).

4.4.2. Variability arising from phonetic context
Different observations were made concerning variability in Gibbon, Dent and Hardcastle (1993). This single case study investigated the EPG patterns of a child (E, aged 9;0 years) whose alveolar targets were perceptually variable. Perceptual judgements of E’s alveolar targets made by twenty listeners confirmed that a degree of variability existed: in some words alveolar targets were heard by listeners as phonological substitutions (/t, d, n/ → [k, g, ɹ]); in other cases, they were heard as normal alveolar productions (/t, d, n/ → [t, d, n]); and in still other cases, they were judged as phonetic distortions (/t, d, n/ → [c, ɹ, n]).

Despite perceptual variability, abnormal tongue-palate contact was observed during all alveolar stop targets (oral and nasal). This abnormality was manifested in the production of complex articulations resembling double velar/alveolar articulations, the approach phase of which was always located in the velar region but with a variable location of the release. It was found that phonetic context affected listeners' judgements, so that where gestures occurred in word-final position, the release of the stop occurred at a relatively anterior location and listeners heard correct alveolars. Conversely, in word-initial position, the location of the release was further back on the palate, with the result that alveolar targets in this phonetic context were more likely to be heard as velar substitutions or palatal distortions (see Gibbon, Dent and Hardcastle, 1993, for further details).
4.4.3. Articulatory sources of variability

A number of different abnormal articulatory phenomena in children with DSD can give rise to perceptual variability. For example, the extent of tongue-palate contact and the details of the start of closure and/or release phases of stops affect listeners’ judgements. The EPG data illustrate clearly how articulatory phenomena frequently underlie apparent variability at the level of phonological organisation, and it may be that much perceptual variability in the speech of children with DSD has an articulatory basis. An articulatory phenomenon underlying perceptual variability has also been reported in EPG studies of adults with acquired neurogenic disorders (Edwards and Miller, 1989; Hardcastle and Edwards, 1992; Wood, 1997). In these studies, the existence of abnormal, intrusive velar gestures in the speech of adult dyspraxics also resulted in variability in perceptual judgements.

4.5. Perceptually normal sounds

The Published Research contains a number of instances where abnormal EPG patterns are observed for sounds that had been judged by listeners as normal, or at least acceptable, productions. Three types have already been exemplified: (i) the temporally abnormal /kl/ clusters (Figure 2b); (ii) the spatially abnormal EPG patterns for alveolar targets (Figure 4); and (iii) the abnormal velar contact observed during stop closure for alveolar targets (Figure 5 and Figure 7b). One further example is given to complement those already presented.

In the Gibbon (1990) study, EPG data from two children with DSD are described. One of the children, VB (aged 6;02 years), was heard to be neutralising many phonological contrasts, although she was judged as having acquired the alveolar/velar contrast and there was no evidence from the case history that VB’s production of alveolars had ever been an area of difficulty. The EPG data, however, revealed that this was another example of broad, undifferentiated tongue-palate contact patterns. Figure 8 shows that VB had appropriate alveolar contact during the start of closure and release phases, but that during the closure phase the tongue body was raised, making full contact in the velar region. At the
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EPG frame of maximum contact (frame 156) there is almost complete contact between the tongue and the hard palate. This type of abnormal EPG pattern was typical of all VB’s productions of alveolar stop targets, and they were consistently heard as acceptable, normal alveolars.

Figure 8. EPG printout of a perceptually normal sound, /d/ → [d]

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Clearly, abnormal articulations do not always result in perceptual misidentifications. Wood’s (1997) research (reviewed in Section 3.4) shows this to be the case in the temporal dimension, where listeners did not identify abnormally long durations produced by a dyspraxic speaker. The EPG data summarised here show that the same applies in the spatial dimension, i.e. that abnormal tongue configurations do not necessarily result in a perceived speech error. Certain sound classes appear to be relatively robust in terms of their perceptual equivalence. For example, alveolar stops can be produced using relatively gross, undifferentiated articulatory gestures, and still remain acceptable productions from the listeners’ perspective (see also the findings of McCarty and Hamlet, 1977). Sibilant targets, however, seem to be particularly fragile, and susceptible to being judged as distorted, even in the context of relatively minor articulatory abnormalities (e.g. the child described in Gibbon and Hardcastle, 1987). EPG patterns for sibilant targets are discussed in the following section.
4.6. Phonetic distortions

Production of lingual fricatives makes great motoric demands on the tongue (Hardcastle, 1976). For their successful articulation, speakers must have the speech motor skill to control both the tongue tip/blade and the tongue body, and in addition to be able to create a precise deformation in the anterior portion of the lingual hydrosstat. It is therefore not surprising that these sounds are highly vulnerable to disruption in children with DSD. In the next section, examples of EPG patterns for lateralised distortions are described, since lateralisation has been the most frequently occurring type of distortion reported in The Published Research. Descriptions of other distortions (palatal and dental) can be found in Gibbon et al. (1995\(^9\)).

4.6.1. Lateralised distortions

Gibbon and Hardcastle (1987\(^1\)) report a single case study describing the EPG characteristics of so-called lateral /s/ in a child with DSD, aged 12;0 years. EPG studies concerning lateral misarticulations at the time of the Gibbon and Hardcastle (1987\(^1\)) study had only investigated cleft palate speech and the findings suggested that these articulations were always produced with abnormal, complete constriction across the palate (Michi, Suzuki, Yamashita and Imai, 1986). Contrary to the EPG results from cleft palate speech, the EPG patterns for the child in the Gibbon and Hardcastle (1987\(^1\)) study unexpectedly showed that a central anterior groove was present during this child’s productions of lateral /s/.

The EPG patterns for /s/ targets were characterised by excessive contact in the palatal regions of the palate and a lack of full tongue-palate contact in the posterior, lateral regions of the palate. A similar type of EPG pattern was recorded in a child aged 11;0 years, as reported in Gibbon, Hardcastle and Moore (1990).

The findings from Gibbon and Hardcastle (1987\(^1\)) and Gibbon et al. (1990) were investigated further in a group of ten children with DSD (see Gibbon et al., 1995\(^9\); and Hardcastle, Gibbon and Scobie, 1995\(^10\), for an account of this cohort’s affricate production). The results showed that lateralised articulations are generally associated with complete contact across the palate, increased tongue-
palate contact, and, for some children, incomplete lateral seal. These findings are consistent with subsequent EPG studies, which have reported similar configurations for lateralis ed productions (Hardcastle et al. 1987; Hardcastle, Morgan, Barry and Nunn, 1989; Suzuki, Dent, Wakumoto, Gibbon, Michi and Hardcastle, 1995). Figure 9 illustrates a typical lateralis ed fricative from D6 (aged 12;03 years) for the production of the word-initial /ʃ/ target in shop (described in Gibbon et al., 1995a). Note the complete midsagittal contact in the alveolar region, the asymmetric skewed configuration in the anterior region and the incomplete posterior, lateral seal on the right-hand side of the palate.

Figure 9. EPG printout of lateralis ed fricative, /ʃ/ → [f]

4.6.2. Articulation in phonetic distortions

The findings reported in The Published Research show that perceptual distortions are usually correlated with EPG spatial distortions, which are in turn characterised by idiosyncratic articulatory configurations. The exact place of articulation and degree of tongue-palate contact varied for individual children with lateralis ed distortions: some had alveolar placement (e.g. D6, in Figure 9); others had broad, undifferentiated contact across the whole of the palate; and one child had velar placement for lateralis ed affricates. A further conclusion from these studies is that certain phonetic details, such as place of articulation and overall extent of tongue-
palate contact, are difficult to detect auditorily in distorted productions. This conclusion is further supported by Dagenais, Critz-Crosby and Adams (1994), who report EPG data from two children with lateral lisps.

5. Implications for the diagnosis of DSD

The EPG data reported in The Published Research, as summarised in Section 4, show that the children investigated produced a wide range of abnormal articulatory gestures, many of which were not detected from auditory analyses. The next section presents the case that the abnormal EPG patterns can be interpreted as evidence for the presence of specific lingual motor control difficulties in the children studied. Three key pieces of evidence support the claim that the articulatory difficulties summarised in Section 4 reflect motor-level (phonetic), and not linguistic-level (phonological), difficulties: (i) the pervasive nature of EPG spatial distortions in the speech of children with DSD; (ii) the subtle timing difficulties evident in stop production; and (iii) the presence of articulatory covert contrasts.

5.1. EPG spatial distortions

EPG spatial distortions were observed in the majority of the children reported in The Published Research publications. In some children, spatial distortions occurred for relatively few sound targets, such as sibilants, and generally involved difficulties with groove formation in the tongue tip/blade region. Difficulties such as these were discrete, and tongue-palate contact patterns for other targets appeared normal (e.g. D3 and D4, Gibbon et al., 1995). Articulatory difficulties of the discrete type are consistent with the traditional view of functional articulation disorders (see Section 2.1.1). However, perhaps more interesting was the unexpected finding that many of the children investigated had spatial distortions that affected a far wider range of target sounds and sound classes than had been predicted from an auditory analysis. EPG distortions that involve broad,
undifferentiated tongue-palate contact occurred in many of children reported in The Published Research. This articulatory characteristic is interpreted as a specific type of speech motor control deficit affecting tongue movement.

5.2. Interpretation of undifferentiated EPG patterns

In broad, undifferentiated tongue-palate contact patterns, anterior tongue-palate contact always occurs simultaneously with posterior contact (see examples of undifferentiated EPG contact patterns in Figure 4, Figure 5 and Figure 7). In other words, tongue tip/blade movement does not occur independently of tongue body movement in these cases. Gestures of this type are characteristic of immature articulatory systems, which during the early stages of speech development operate according to the “everything moves at once principle” (Kent, 1983, p. 70), whereby sets of articulatory gestures are produced in a largely synchronous manner. One characteristic of mature lingual control (at least in adult speakers, see Section 3.3) is that the tongue tip/blade and the tongue body articulators do not always move together, but are co-ordinated to overlap in time and demonstrate the ability to occur relatively independently of each other. The finding that some children are unable to raise the tongue tip/blade without simultaneously raising the tongue body indicates the presence of a specific lingual motor control difficulty.

5.2.1. Motor control and the lateral regions of the tongue

Children with broad EPG contact patterns appear to have additional motor difficulties in the control of lateral and medial regions of the tongue. In order to produce normal alveolar stops, children need to be able to “tense the lateral borders of the tongue to produce a spoon-shaped configuration” (Fletcher, 1992, p. 99). Stone (1991) proposes that in order to accomplish this lateral bracing, the medial and the lateral components of the tongue are controlled semi-independently. Broad, undifferentiated EPG patterns involve complete contact between the tongue and the hard palate, an articulatory configuration which precludes the possibility of either lateral bracing or the formation of the central,
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concave depression of the tongue surface characteristic of normal alveolar production (Fletcher, 1992; Hardcastle, 1976).

Stone, Faber, Raphael and Shawker (1992) suggest that control of the lateral margins of the tongue is important, since lateral anchorage gives stability to the whole of the tongue. The implication is that lack of lateral control will have a significant effect on the development of normal speech motor control. Furthermore, the ability to produce normal alveolar stops is thought to underpin the subsequent development of other gestures. Fletcher (1992) maintains that the ability to produce normal anterior stops is a prerequisite for the development of velar and sibilant sounds, stating that “the anterior stop gesture is postulated to serve as a fountainhead for the remaining lingual consonant gestures” (Fletcher, 1992, p. 99). Thus, a speech motor control deficit that results in abnormal articulation of alveolar stops is predicted to affect subsequent development of other sounds (particularly sibilant sounds).

There is some EPG evidence in The Published Research that supports Fletcher’s (1992) view, since none of the children with undifferentiated tongue-palate contact for stops produced grooved alveolar fricatives. For example, VB and MB (Gibbon, 1990) had broad EPG contact for alveolar stops and both used the phonological process of fricative gliding (see Figure 5). However, the EPG data are not unequivocal in their support of Fletcher’s (1992) hypothesis. The child E (Gibbon, Dent and Hardcastle, 1993) produced normal alveolar fricatives (a judgement based on both perceptual and EPG data), but she did not have normal alveolar stops. D2 (Gibbon et al., 1995) had the opposite pattern, producing normal alveolar stops but abnormal alveolar fricative targets (palatal distortions). It may be that the ability to control tongue tip/blade and tongue body gestures sufficiently to produce discrete alveolar stops facilitates, but does not necessarily guarantee, subsequent emergence of normal alveolar fricative gestures.

5.2.2. Pervasive nature of undifferentiated gestures

Children who produce broad, undifferentiated gestures, tend to do so for a wide range of targets, with different perceptual consequences: some targets are heard by listeners as normal sounds (see examples in Section 4.5); some are heard as
phonological substitutions (see Section 4.3); and some as phonetic distortions (see Section 4.6). The finding that undifferentiated gestures occur for a wide range of targets is further support for the claim that broad contact patterns reflect an underlying, pervasive speech motor control difficulty, a difficulty that could be expected to have implications for a child’s ability to develop normal speech in the future.

Variable and relatively undifferentiated EPG patterns have been reported to occur in children with clear organic pathology, such as developmental dysarthria (Hardcastle et al., 1987). In the Hardcastle et al. (1987) study, variable EPG patterns were interpreted as indicating that the child had “little control over the different functional parts of the tongue and that it moves about the oral region as a single undifferentiated mass” (p. 180). The inconsistent EPG patterns produced by the child in the Hardcastle et al. study were thought to be compatible with the speech diagnosis of hypotonic dysarthria that had been made in this case. The finding that undifferentiated EPG patterns occur in many children with speech disorders of unknown origin lends further support to the proposition that speech motor control deficits underlie at least a significant proportion of DSD.

5.3. Lingual timing difficulties

Several illustrations in Section 4 demonstrate that broad, undifferentiated EPG patterns are frequently coupled with difficulties in the timing of the approach and/or release phases of stops. During undifferentiated gestures, the tongue tip/blade and the tongue body move to make contact with the hard palate. Indeed, whole tongue gestures allow for the possibility for approach and release phases to occur in either anterior or posterior regions. The various combinations of alveolar/velar approach and release phases are illustrated in Figure 6a and Figure 7. Abnormal timing of approach/release phases appears to result in complex and unreliable perceptual cues, resulting in variability at the perceptual level.

Timing difficulties and undifferentiated articulatory gestures (described in Section 4) provide a persuasive articulatory explanation of the variable speech errors that are frequently reported in the literature on child phonology and
phonological disorders. For example, studies of the speech of children with DSD show many instances of the type of perceptual variability displayed by MB (Gibbon, 1990) and E (Gibbon, Dent and Hardcastle, 1993). Of the seven children with phonological disorders described in Grunwell (1981), all but one show instances of perceptual variability of alveolar and velar stop targets in the data sample provided (see Table 1).

<table>
<thead>
<tr>
<th>Subject details</th>
<th>Target</th>
<th>Transcription</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joanne (5;00 years, p194)</td>
<td>dog</td>
<td>dod; god</td>
</tr>
<tr>
<td></td>
<td>doll</td>
<td>dol; gol;</td>
</tr>
<tr>
<td></td>
<td>tent</td>
<td>tent; kent²</td>
</tr>
<tr>
<td>Darren (6;03 years, p202)</td>
<td>Christmas</td>
<td>'ki?bə; 'di?bə;</td>
</tr>
<tr>
<td>Paul (6;11 years, p 208)</td>
<td>cap</td>
<td>ka; tap¹</td>
</tr>
<tr>
<td></td>
<td>cart</td>
<td>ta; ka</td>
</tr>
<tr>
<td>Tanya (8;0 years, p 212)</td>
<td>candle</td>
<td>'tanu; 'kanu</td>
</tr>
<tr>
<td>David (5;08 years, p 217)</td>
<td>cage</td>
<td>ker; tet</td>
</tr>
<tr>
<td></td>
<td>cake</td>
<td>ker; tet</td>
</tr>
<tr>
<td>Pamela (7;2 years, p 220-221)</td>
<td>cake</td>
<td>geik; deik</td>
</tr>
<tr>
<td></td>
<td>cart</td>
<td>kck</td>
</tr>
</tbody>
</table>

5.3.1. An articulatory mechanism for puzzles

The possibility that subtle timing difficulties and undifferentiated articulatory gestures might occur in the speech of young children is not generally recognised by those who rely entirely on standard transcription for data analysis. However, it may be that this type of articulatory immaturity is widespread in child speech, and that the presence of timing difficulties contributes to the perceptual variability frequently noted in the literature. Recall that Smith (1973, cited in Section 2.1.1) used the observation that Amahl could correctly produce sounds in some contexts as an argument against a phonetic (motoric) explanation of his son’s speech errors. Smith’s view was that articulatory difficulties alone were insufficient to account for sound substitutions, stating that his son Amahl appeared:

unable to produce a particular sound or sound sequence in the correct place, but [was] perfectly capable of producing it as his interpretation of something else. (Smith, 1973, p. 4.)
Based on the EPG evidence presented in Section 4, there is an alternative, articulatory account for Smith’s *puzzle* phenomenon. It could be that Amahl produced broad, undifferentiated gestures for both /d/ and /z/ targets. The gesture for /d/ (heard as [g], *puddle* → *[pashington]*) could have involved velar contact in the approach and the release phases (similar to Figure 6a), whereas the gesture for /z/ (heard as [d], *puzzle* → *[pashington]*) could have involved contact in the alveolar region during these phases (similar to Figure 8). In other words, it may be that Amahl was not ‘perfectly capable’, in motoric terms, of producing /d/ in any context.

According to Smith, Amahl produced *puzzles* with “completely regular rules” (Smith, 1973, p. 4), which begs the question of why the approach and/or the release phases might be different for /d/ and /z/ targets. It is only possible to speculate about this, but it could be that Amahl adopted an articulatory mechanism for alveolar stop production similar to that adopted by E (described in Gibbon, Dent and Hardcastle, 1993). In E’s productions, the approach phase of alveolar stop targets always occurred in the velar region, followed by EPG contact that moved forward into the alveolar region during closure. In word-final position, alveolar targets were more likely to be heard as normal alveolars, since in this context the tongue contact had time to move forward into the alveolar region and this in turn increased the probability of an alveolar release. If in Amahl’s case, /z/ targets were longer in duration than /d/ targets, then this would increase the likelihood of an alveolar release, and hence increase the chance of an alveolar percept for these targets. Whilst Amahl’s actual articulation during *puzzle* and *puddle* will never be known, the EPG evidence suggests an articulatory mechanism that could be responsible, at least in principle, for the *puzzle* phenomenon.

5.4. Covert contrasts

The implications of covert contrasts have not been discussed extensively in the child phonology literature. However, Gibbon and Scobbie (1997) have argued that the presence of covert contrasts reflects: (i) ‘productive phonological knowledge’
of the contrast; and (ii) inadequate motor control for adult-like realisations of the relevant phonetic categories (for further discussions see Gibbon, 1990³; Gibbon and Scobbie, 1997; Edwards, Gibbon and Fourakis, 1997¹³). In other words, covert contrasts are evidence that the underlying deficit is phonetic, and not one of learning the underlying phonological rules of the language, i.e. a cognitive/linguistic disorder (this issue is discussed further in Section 6.2.1).

The EPG evidence of the presence of articulatory covert contrasts raises doubts about the origin of at least a proportion of speech errors that are assumed to reflect cognitive/linguistic difficulties. The EPG data presents articulatory evidence that some phonological errors reflect motor control problems. Further, many claims commonly made about articulation in children based on transcription data need to be examined carefully in the light of the EPG data presented. A recent example is from Berg (1995), who states in relation to auditory-impressionistic transcription of the alveolar/velar contrast in child phonology:

/k/ and /g/ ... are generally replaced by stops articulated further to the front of the mouth, in particular /t/ and /d/. Because different articulators are involved, such place-of-articulation changes as /k/ to /t/ cannot really be continuous .... This discreteness makes it comparatively easy to distinguish between correct and incorrect productions of the child on-line. (Berg, 1995, pp. 334-335.)

The EPG data suggest that Berg's view is simplistic and potentially mistaken. Certainly it is the case that in disordered speech it is often difficult to distinguish velar from alveolar places of articulation (Gibbon, Dent and Hardcastle, 1993³); and the distinction between 'correct' and 'incorrect' becomes equally problematic in the light of articulatory abnormalities (most notably broad, undifferentiated tongue gestures and their variable approach and release phases) reported in The Published Research (see Edwards et al., 1997¹³, who reply to Berg's statement).
6. Implications for theories of speech development and disorders

Section 5 showed how the studies of Gibbon, Hardcastle and Nicolaidis (1993) and Hardcastle et al. (1996) led to important insights about tongue tip/blade and tongue body control in children with DSD. In this section, the EPG findings from the children with DSD are interpreted in order to show how speech motor control of the tongue might emerge in young normally developing children. Many view the speech of children with DSD as being quantitatively, but not qualitatively, different from that of normal children (Hodge, 1993). If children with DSD are delayed rather than deviant in their motor skills, then it is possible that lingual control difficulties of the type summarised in Section 4 occur in normally developing children, but at an earlier stage of development.

6.1. Implications for normal development of lingual articulation

Although much is known about lingual control in adults, less is known about its development in young children. However, studies are beginning to show how speech motor control of the tongue might develop in infants. For example, an acoustic study by Hodge (1989, cited in Kent, 1992) showed that alveolar articulations such as /dæ, dæ, dæ/ produced by infants (7-9 months) are performed largely by a passive tongue ‘riding’ on the active mandible. This has been used as evidence that infants at the babbling stage do not have independent motor control of the tongue and the jaw (Kent, 1992).

Evidence that independent tongue/jaw control develops following the babbling stage comes from mastery of the high vowels /i/ and /u/ during the second year of life. Production of high vowels may be more demanding than the low or the mid-vowels, which dominate vocalisations in the first year of life. For example, high vowels involve extending the tongue in some regions, accompanied by a narrowing in the lateral dimension (Kent and Hodge, 1991). Independent tongue and jaw control is required in order to achieve accurate tongue height for /i/ and /u/ vowels in different consonantal contexts, an accomplishment which
occurs during the second year of life in normally developing children (Kent, 1992).

Once tongue movement is controlled relatively independently of jaw movement, there is evidence suggesting that the tongue may function as a single articulator, as opposed to two separately controllable articulators. Indirect evidence for this stage comes from studies by Davis and MacNeilage (1990; 1994) who investigated consonant-vowel interactions in normally developing children at the babbling and the first words stages of speech development. Davis and MacNeilage (1994) found two dominant patterns of co-occurrence of consonant and vowels that involved the tongue: consonants transcribed as alveolar stops tended to occur with front vowels; and velars tended to occur with back vowels. Constraints such as these on the CV syllable led MacNeilage (1997) to conclude (in relation to consonants and vowels in the early stages of speech development), that “these major classes [consonants and vowels] are not under independent control” (p. 313). One interpretation of this constraint on the CV syllable is that the tongue at this stage of development operates as a single articulator.

If it is the case that in infants the tongue functions as a single articulator, and in adults it functions as two articulators (see Section 3.4), it is reasonable to suggest that during the period of speech development motor control of the tongue tip/blade and the tongue body gradually develops.

6.1.1. Development of lingual control for alveolar stops

Articulation of normal alveolar stops requires sophisticated lingual control, since execution requires bending of the muscular hydrostat (Stone, 1991; Fletcher, 1992) and the ability to control the tongue tip/blade independently of the tongue body (Hardcastle, 1976). It is also well established in the literature that alveolar stops are one of the first classes of sounds to be ‘mastered’ by normally developing children (e.g. Sander, 1972). Is it the case that children have acquired advanced tongue control at the earliest stage of speech development? The answer is: not necessarily. Perhaps during the early stages of speech development, alveolar targets are produced with relatively gross, undifferentiated articulatory gestures, similar to those of D8 (Figure 4) and VB (Figure 8). Undifferentiated
tongue gestures of this type could be produced when lingual control is at a relatively early developmental stage, i.e. when the tongue functions as a single articulator, and still be heard by listeners as acceptable alveolar productions. How might control for alveolar stops proceed in normal development?

6.1.2. Hypothetical stages in the development of alveolar stops

Hypothetical stages of the articulatory development of alveolar stops, as they might be revealed by EPG, are shown in Figure 10.

*Figure 10. Hypothetical stages in the articulatory development of alveolar stops*

In Figure 10, Stages II-VII of phonological development are shown on the left. The stages are from Grunwell (1981), and are generally accepted as reflecting...
phonetic inventories of normally developing English children from the period following the first fifty words to the completion of their inventories. The phonetic inventories of lingual stops and fricatives, and the phonological processes that frequently affect these sound classes, are shown in the central column of the figure. To the right of the diagram are schematic EPG patterns, as they might appear at the point of maximum contact during the production of alveolar stops at the different stages of development.

At Stages II/III broad, undifferentiated tongue gestures are the only articulations available to the child, and they are used for a wide range of targets. Tongue movements at this stage have immature speech motor control, and could be described in terms of “everything moves at once” (Kent, 1983, p. 70). At this stage listeners may hear undifferentiated gestures as acceptable alveolar stops, e.g. as instances of [d]. Where these [d]s occur in words that contain /d/, they will be treated by listeners as “hits” (Locke, 1983, p. 83). Similar, i.e. undifferentiated, gestures may be used for other targets, and these will be heard as errors such as phonological substitutions (e.g. fronting of velars and stopping of fricatives). A certain degree of perceptual variability is expected at this stage, due to inconsistent timings of the approach and the release phases of stop production.

Developments in lingual control from Stage IV occur in the context of great changes in anatomy in the oral area from the third year of life onwards. Anatomical developments involve a combination of tongue retraction into the pharyngeal region, concurrent with an expansion in the lateral dimensions of the palatal alveolar processes and an increase in the height of the palatal vault, resulting in an expansion in the space within which the tongue can move (Bosma, 1975).

At the same time that the oral cavity enlarges, the tongue elongates in the apical region, developing a “limblike mobility” (Bosma, 1963, p. 101), which is paralleled by growth in nerve myelination in the intrinsic lingual musculature. The combination of increased oral space, rapid increases in movement potential in the tongue tip/blade regions, and the expansion of tactile, kinaesthetic feedback capacity all facilitate the progressive emergence of motor control of the two
tongue systems. The descent of the posterior region of the tongue into the developing pharyngeal cavity and the increase in height of the hard palate act to diminish the likelihood of broad undifferentiated tongue-palate contact occurring. Contrary to current views in the child phonology literature, the account of alveolar stop development outlined above suggests that normal alveolar stop articulation is not accomplished until a relatively late stage in normally developing children.

6.1.3. Development of tongue tip/blade and tongue body coarticulation

From a biological perspective, processes of differentiation and integration play an important role in speech acquisition (Kent, 1992). Such processes can be observed in the development of tongue control: differentiation would involve the development of independent control in different regions of the tongue (see Figure 10 for an illustration of how this might emerge for alveolar stops); integration would involve the development of the ability to combine tongue movements to produce co-ordinated gestures. Ultimately, speed and efficiency of movement increase as lingual motor control develops, resulting in tongue movements which are able to meet the spatial and the temporal requirements for tongue tip/blade and tongue body articulations. An illustration of the articulatory skills that children have acquired by the age of 12 years is shown in Figure 11.

Figure 11. Normal child's production of the /kt/ sequence in tractor

![Figure 11](image)

Figure 11 shows EPG data from a normally developing child (N1, aged 12;03 years, from Gibbon et al. 1995) during production of a word-medial /kt/ sequence.
in tractor. The printout shows tongue-palate contact for tongue tip/blade and tongue body movement during the consonant sequence, and illustrates the phenomenon of coarticulatory overlap (frames 224-232) which enables the /kt/ sequence to be produced in a fast and efficient way. Unlike the children with developmental speech disorders described in Section 4, this child has clearly acquired the speech motor skill to “control the tongue to meet skeletal, movement, and shaping requirements … simultaneously” (Kent, 1992, p. 72).

6.2. Psycholinguistic models

The overall finding that the children investigated show a range of speech motor deficits is contrary to the currently popular view of DSD, and as a result there is a need to turn to theories that emphasise the role of phonetic skills. The following sections discuss the contribution of The Published Research to two recent approaches to speech development and its disorders: (i) psycholinguistic approaches, including a newly revised model proposed by Hewlett, Gibbon and Cohen-McKenzie (in press); and (ii) a dynamic systems model (Thelen, 1991).

6.2.1. Underlying representations

The EPG data reported in The Published Research have been used as evidence to show how target phonological categories might be represented in children’s mental lexicons (e.g. Butcher, 1996; Hewlett et al., in press). The existence of covert contrasts is widely interpreted as powerful evidence that target phonological contrasts are stored as separate underlying representations (for further discussion, see Gibbon and Scobbie, 1997; Wells, 1995). It would be difficult to explain the articulatory differences observed in covert contrasts for target phonological categories if this were not the case. Concerning the storage of underlying phonological representations, there has been considerable debate in the literature about whether children have two separate lexicons, one for perception and one for production, or whether there is one common lexicon underlying both capacities. Hewlett et al. (in press) and Butcher (1996) embrace the notion of a single lexicon, citing EPG data from The Published Research as supporting
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evidence. Hewlett et al. (in press) view the presence of alveolar/velar covert contrasts, of the type described in Gibbon (1990), as evidence against a separate output lexicon, concluding that:

since both articulations (i.e. t-like articulations of /t/ targets and t-like articulations of /k/ targets) must presumably derive from a specification CORONAL and [+ anterior] in the Output Lexicon, the possibility of allowing for a difference between them is thereby lost. (Hewlett et al., in press.)

The precise content of phonological representations in the single lexicon is discussed in Hewlett et al. (in press), where it is proposed that entries have mainly acoustic-perceptual content, rather than articulatory content, as is often assumed. There are advantages to positing acoustic-perceptual representations. This arrangement allows for the possibility that a child may possess productive knowledge of phonological categories but not necessarily the speech motor skill to execute those categories in such a way as to give a satisfactory acoustic result. The proposal that the origin of errors is motoric is consistent with the overall EPG findings from The Published Research, as summarised in Section 4.

6.3. Dynamic systems theory

A dynamic systems approach to speech acquisition attempts to describe processes that give rise (or fail to give rise) to new forms of behaviour (Kent and Hodge, 1991; Thelen, 1991). The theory can therefore provide a framework within which to place the finding that children with DSD have specific speech motor control deficits. Dynamic systems theory (Fowler, Rubin, Remez and Turvey, 1980; Kelso, Saltzman and Tuller, 1986) has much in common with theories of task dynamics (Tuller and Kelso, 1984) and other theories generically termed biological (e.g. Kent, 1992; Kent and Bauer, 1985; Locke, 1980; 1983).

6.3.1. Attractor states

A key concept in dynamic systems theory is the existence of stable articulatory movement configurations, termed attractor states, in speech production. Attractor states are preferred movement configurations for structures such as phonetic
segments or features (Kent and Hodge, 1991). Articulatory configurations may be likened to co-ordinative structures (Tuller and Kelso, 1984) and articulatory routines (Browman and Goldstein, 1989; Menn, 1983). The selection of movement configurations into attractor states is accomplished by infants being sensitive to the sensory consequences of their own motor actions, information which is used to select and to refine subsequent articulatory movements.

Attractor states are selected and become stable when there are good matches between different types of sensory information (e.g. auditory, visual, tactile, kinaesthetic, etc.) and where an action achieves a successful communication. At any one point in time, movement configurations other than those in stable attractor states may be possible, but they may not become attractor states themselves because they are perhaps more difficult motorically for the child to execute. Speech development is thus seen as a series of emerging and dissolving attractor states, which emerge or dissolve under the influence of ‘disrupting forces’.

6.3.2. Disrupting forces

New levels of articulatory complexity arise from the disruption of stable attractor states. Factors which disrupt existing states, and thus facilitate further development of articulatory complexity include: anatomical changes in the vocal tract; increased speech motor control; increasingly sophisticated perceptual skills; and developing abilities in category formation and multi-modal matching. Multimodal matching in dynamic systems theory is thought to underpin speech development, and it involves the ability to form links between auditory-visual, tactile-visual, auditory-kinaesthetic, and other modalities of perception and production of speech. Thelen (1991) states that in speech development “both the (articulatory) movement and its visual, proprioceptive, auditory and tactile consequences continuously converge and are correlated” (p. 346). Initially, multimodal matches between perception-production correspondences (auditory-motor, auditory-visual, motor-visual, etc.) are broad and relatively undifferentiated. However, the links between the correspondences become progressively refined.
and integrated, through children's regular exposure to the ambient language, and their day-to-day experience of talking.

6.4. Dynamic systems account of DSD

The main characteristic of children with DSD is that their progress in speech is outpaced by development in other areas. Within the framework of dynamic systems, this lack of progress can be viewed as speech remaining in stable, but immature or abnormal, attractor states.

6.4.1. Immature attractor states in DSD

Two possibilities emerge as reasons why children with DSD fail to make progress in speech development: (i) the failure of disruptive forces to dissolve existing attractor states; and/or (ii) overly powerful attractor states that do not dissolve, despite the presence of normal disruptive forces. Taking the first possibility, the evidence from The Published Research suggests that many of the children studied had speech motor control difficulties. This finding adds to the accumulating instrumental evidence that points to the existence of phonetic (motor and perceptual) difficulties in a significant proportion of children with DSD (e.g. Catts and Jensen, 1983; Edwards, 1992; Waters, 1992; Watson, 1997; Weismer and Elbert, 1982).

The second possibility is that attractor states themselves are inherently too strong, or too inflexible, to dissolve, even when normal disruptive forces are present. The evidence from The Published Research suggests that attractor states, however they come about in the first instance, are both powerful and inflexible. The fact that the children reported throughout The Published Research had intractable speech difficulties, despite receiving speech therapy, points to an inflexible articulatory system. Further evidence comes from the well-known problem of lack of carryover of newly acquired articulatory patterns into natural speech, a problem that occurs in speech pathology and second language learning (see Gibbon, Hardcastle and Suzuki, 1991), who used EPG to assist Japanese students learn the English /r/ - /l/ distinction).
6.4.2. Modifying stable attractor states

Attractor states are stable, which is an advantage to normal speakers since this stability allows speech to become controlled at an increasingly automatic level. However, when attractor states are abnormal, their existence is a distinct disadvantage since it is well-known that "old motor habits die hard" (Butcher, 1996, p. 72). Although attractor states are stable, they are not completely inflexible. The evidence in The Published Research is that children with DSD are able to change established articulatory movement configurations, and that change is greatly assisted by the use of visual feedback of the type provided by EPG (see Dent, Gibbon and Hardcastle, 1995; Gibbon, Dent and Hardcastle, 1993; Gibbon and Hardcastle, 1987; Gibbon and Hardcastle, 1989; Gibbon et al., 1991; and see Dagenais, 1995, for a review of the first two publications).

EPG provides an additional sensory modality not usually available during speech acquisition, in the form of direct, real-time visual feedback of tongue position and movement. Visual information can be used to generate new articulatory configurations, which can be correlated, or matched, with their auditory, tactile and proprioceptive consequences. In terms of dynamic theory, visual feedback acts as a powerful disruptive force, enabling children to dissolve out of immature, inflexible attractor states and emerge into different – and in the case of children with speech disorders, more normal – articulatory configurations.

6.4.3. Attractor states in osteotomy

Dynamic systems theory predicts that as children get older, attractor states become more stable and increasingly difficult to disrupt, and so it is relevant to investigate adult cases. An ideal opportunity to study articulatory stability in adults arose during a project in which EPG was used to investigate the effects of orofacial surgery on articulation. In a study by Wakumoto, Isaacson, Friel, Suzuki, Gibbon, Nixon, Hardcastle and Michi (1996), changes in articulatory placement were measured in patients undergoing osteotomy, an operation that involves radical changes to the skeletal relationship between the mandible and the maxilla.

Wakumoto et al. (1996) found that articulatory placement changed following the operation, and that the direction of change could be predicted on the
basis of the operation undergone. Wakumoto et al. found that there was a passive shifting of articulatory placement backwards or forwards, depending on the direction in which the mandible was moved (as a result of surgery) in relation to the maxilla. The results of this study suggest that movement configurations, or attractor states, established at the time of surgery, were stable since they showed no evidence of reorganisation following surgery. The patients in the Wakumoto et al. (1996) study did not have any form of speech disorder pre- or post-operatively, and although there were subtle acoustic changes, speech did not alter perceptually following surgery. It appeared that the changes in speech that occurred as a result of surgery were insufficient to disrupt well-established attractor states. It would be of interest to know whether articulatory reorganisation occurs where osteotomy results in a deterioration in the perceptual quality of patients' speech.

7. Summary and conclusions

Given the unique anatomical properties of the tongue and the complexities involved in controlling temporal and spatial aspects of its behaviour, it is perhaps not surprising to find evidence of disrupted tongue control in children with DSD. Further research is clearly required to specify more precisely the exact nature and extent of motor control difficulties in individual children. However, the specific lingual control deficits reported in The Published Research represent a significant advance in the pursuit of the origins of DSD.

The findings from the EPG studies have wide-ranging implications for the assessment of DSD, many of which are discussed in The Published Research publications (see Gibbon, 1990; Gibbon, Dent and Hardcastle, 1993; Gibbon and Hardcastle, 1987; Hardcastle and Gibbon, 1997). The findings show how speech motor control difficulties can underlie apparent phonological errors as well as phonetic distortions in the speech of children with DSD. Thus, it may be that the distinction between phonological and phonetic speech errors is more apparent to transcribers than a real reflection of distinct underlying deficits.
It is probable that motor deficits have been greatly underestimated in many studies, due to the widespread use of methodologies that are inadequate for the purpose of measuring speech motor control. For example, motor control deficits that result in broad undifferentiated tongue-palate contact patterns are not captured readily with the type of alphabetic notation commonly used to characterise children’s speech disorders. As a result, there is an urgent need to validate findings from non-instrumental tasks (e.g. diadochokinetic rate, non-speech oral movements, perceptual judgements about the accuracy of non-word production) that are commonly used to identify motor deficits. Findings from such tasks need to be correlated with instrumental data (e.g. acoustic analysis and EPG) in order to establish their reliability in detecting speech motor deficits.

The proposed stages of normal lingual control development outlined in Section 6.1.1 are speculative, and they clearly require further investigations. However, if development of lingual control proceeds in the way outlined in Section 6.1.2, then the different types (e.g. discrete and widespread) of lingual control difficulties experienced by children with DSD may reflect different stages of development of motor control. In other words, children with widespread control difficulties have lingual motor skills that are more delayed than in those with discrete difficulties. An extension of this hypothesis is that children with the diagnosis of developmental verbal dyspraxia represent the severely immature end of the speech motor control continuum. The implication is that children with dyspraxia may be quantitatively, but not qualitatively, different from those with phonological impairment and functional articulation disorders. The study of children’s vowels and consonant-vowel constraints is particularly relevant to the investigation of lingual control in those suspected of having speech motor control deficits. It may be that abnormalities in these aspects of development reflect very early lingual control capabilities. This finding would have important implications for the significance of vowel problems in the speech of children with DSD.

The concept of lingual control as an emergent process as proposed in Section 6.1.1 is supported by much of the general developmental literature on motor control (Kent, 1992). The notion of continuity in development has clinical
implications insofar as “one can predict behavior at a later point in development from an appropriate behavioral organization at an earlier time” (Kent and Hodge, 1991, p. 26). If the children with discrete motor difficulties have more advanced lingual control than those with widespread difficulties, as has been suggested, then it follows that the former group should respond more quickly to therapy, and have a better outcome, than the latter group. This prediction is borne out in studies reporting how children with different speech motor skills respond to EPG therapy (see Dent et al., 1995; Gibbon, Dent and Hardcastle, 1993).

The emphasis on the role of speech motor control in DSD does not represent a wholesale return to earlier conceptions of dyslalia and functional articulation disorders described in Section 2.1, where the difficulty was considered to be with the production of individual speech sounds. Although some children could be described as having articulatory difficulties of such a discrete type, many had a more widespread speech motor control deficit that affected temporal and spatial aspects of lingual movements across-the-board, resulting in perceptually complex and highly individual speech output characteristics.

References

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