Complexity Promotes Changes in Phonological Patterns: Evidence from Behavioral and Neurophysiological Measures

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Abstract of thesis entitled:

Complexity promotes changes in phonological patterns: Evidence from behavioral and neurophysiological measures

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Speech sound acquisition is important for the development of spoken language. One of the longstanding debates in the field of Linguistics is whether speech sound development is driven by exposure to complexity in input or by exposure to simple speech input. Traditional theories (e.g., behaviorist theories, scaffolding theories, connectionist theories, dynamic systems theory) suggest that speech sound development is facilitated by exposure to simple speech sounds first. On the other hand, linguistic-based complexity theories (e.g., generative phonology, natural phonology, optimality theory) suggest that it is the exposure to complex input first that necessitates speech sound development. However, still there is no consensus on whether it is complex input or simple input that promotes acquisition. In the current dissertation, I address this research question via four different approaches that include *Meta-analysis, Maximum Entropy grammar modeling (MaxEnt), Artificial language training,* and *Speech therapy.*

In the meta-analysis study (Chapter 2), data were extracted, processed and combined from 15 selected studies from the literature on treatment of speech sound disorders. Meta-analysis suggested that treatment with complex speech sounds not only improves the production of complex sounds but also generalizes to production of untreated simple speech sounds. In

comparison, treatment with simple speech sounds only leads to improvement in the production of simple speech sounds but does not generalize to untreated complex sounds.

In the MaxEnt study (Chapter 3), 3-6-year-old typically developing children (n=30) and those with speech sound disorders (n=31) were compared on their trajectory of phonological development, analyzed using MaxEnt. Based on the patterns of development, it was found that within the group of speech sound disorders, there existed "deviant" and "delayed" subtypes. Children with "delayed" profiles showed a trajectory of development similar to typically developing children while those with "deviant" profiles showed a different trajectory compared to typically developing children. As one of the pre-requisites for success of complexity therapy in speech sound disorders is the similarity of trajectory of development with that of typically developing children. These findings shed light on the use of complex versus simple input in the therapy of different patterns of phonological development.

In the artificial language training study (Chapter 4), Cantonese-speaking adults trained with complex stimuli (n=48) were compared (using behavioral and electrophysiological measures) with those trained with simple stimuli (n=48) in a pseudoword-picture association learning paradigm. We found that the subjects who were trained on complex stimuli showed improvement in complex stimuli and generalization to simple stimuli while those trained on simple stimuli showed improvement in simple stimuli without showing any generalization to complex stimuli.

In the speech therapy study (Chapter 5), children with speech sound disorders from Cantonese-speaking homes were provided therapy with either complex (n=3) or simple (n=2) speech sounds. It was found that the children who were provided therapy with complex speech sounds improved in complex speech sounds and generalized to untreated simple speech sounds. On the other hand, the children provided therapy with simple speech sounds improved in simple speech sounds but did not generalize to untreated complex speech sounds.

These four studies, corroboratively, indicate that complexity induces widespread generalization to elements with equivalent and/or lesser complexity across the phonological system. Overall, from the findings of this dissertation, it can be concluded that complex input is potentially more efficient than simple input in promoting behavioral and neural changes in the phonological system. The current findings have implications for education and rehabilitation. Traditionally, it is believed that exposure to simple stimuli first followed by a sequential increase in complexity leads to the acquisition of new concepts. In light of the current findings, one can speculate the use of complex stimuli first for a time-effective learning process.

學位論文摘要

學位論文題目： **語言複雜性促進音韻模式轉變：基於行為及神經心理的測量論證**

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語音習得對口語發展至關重要。在語言學界，其中一個歷久不衰的爭論就是到底複雜語音輸入還是簡單語音輸入推動了語音發展。傳統理論，如行為主義理論、鷹架理論、聯結主義理論以及動態系統理論，均認為簡單語音的輸入首先推動了語音發展。然而，基於語言學的複雜性學說，如生成音系學、自然音系學以及優選論，則認為複雜語音輸入才是語音發展的關鍵。對於這一辯題，學界眾說紛紜。本文將採取以下四種方法探討這一問題：*元分析*、*最大熵模型*、*人工語言訓練以及言語治療*。

第二章元分析研究選取了 15 篇有關治療語音障礙的文獻，並對文中數據進行提取、處理與整合。元分析研究顯示，採取複雜語音輸入的治療方式，不僅可以改善此類語音輸出，更可泛化至未經治療的簡單語音輸出。相比之下，採取簡單語音輸入的治療方式則只能改善簡單語音輸出，並不能泛化至複雜語音輸出。

第三章最大熵模型研究則採取了最大熵模型來分析比較年齡為 3 至 6 歲的 30 位發展正常的兒童與 31 位患有語音障礙的兒童的音韻發展軌跡。結果顯示，在 31 位患有語音障礙的兒童中，存在著「發展異常」與「發展遲緩」兩種類型。後者的音韻發展軌跡與正常兒童相差不遠，前者則大相徑庭。有鑒於音韻發展軌跡的相似性能決定

語音障礙治療的成功與否，本文初步探討了複雜語音輸入的治療方式還是簡單語音輸入的治療方式，能更有效針對不同模式的音韻發展語音障礙。

第四章人工語言訓練採取圖文（假字）學習模式，邀請 96 名以粵語為母語的成人分別參與以複雜語音（n=48）或簡單語音（n=48）為內容的訓練，測量並比較他們的行為及生理電信號。研究發現，接受了以複雜語音為訓練內容的被試者，在複雜語音習得上有所改善，並且可習得簡單語音；但以簡單語音為訓練內容的被試者，只在簡單語音習得上有所改善，並無泛化現象。

第五章言語治療研究邀請了兩組患有語音障礙，並且以粵語為母語的兒童接受複雜語音治療（n=3）或簡單語音治療（n=2）。結果顯示，接受複雜語音治療的兒童無論在複雜語音還是未經治療的簡單語音輸出都有所改善。另一方面，接受簡單語音治療的兒童則只在簡單語音輸出有所改善，並無泛化現象。

以上四項研究表明，在音韻系統中，複雜性可以引起同等複雜程度間和/或由繁至簡的泛化。綜上所述，複雜語音輸入，比簡單語音輸入，更有效推進音韻系統的行為與神經變化。傳統觀點認為由易到難的內容輸入，能有助獲取新知識。但本研究顯示，首先輸入複雜的內容也許能加快學習進程。這一點對於教育理論與復康理論具有深遠意義。

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At this juncture, I understand that this milestone has not happened solely as a result of my work in the past five years. I believe that the education and resources provided by my parents right from the days of my primary school played an immense role and ‘thanks’ is not enough for their efforts. Further, I would also like to thank my extended family, the Sharma family, for their consistent support as always. There were crucial periods where their support was pivotal.

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Chapter 1

Introduction

Speech sound acquisition is central to spoken language and is currently a subject of debate in the field of Linguistics. An unresolved research question in the area of speech sound acquisition is whether it is exposure to complex input first that drives speech sound acquisition, or it is exposure to simple input first that facilitates speech sound development. Complex input refers to speech sounds that are typologically more marked/later acquired/less stimulable while simple input refers to speech sounds that are less marked/early acquired/more stimulable. The traditional view of speech sound development (e.g., behaviorist theories, scaffolding theories, connectionist view, dynamic systems theory) suggests that exposure to simple input before complex input is the most important for speech sound development while the recent linguistic-based complexity theories suggest that exposure to complex input (Gierut, 2007; Gierut, Elbert, & Dinnsen, 1987; Gierut, Morrisette, Hughes, & Rowland, 1996; Morrisette, Dinnsen, & Gierut, 2003; Powell, Elbert, & Dinnsen, 1991; Tyler & Figurski, 1994) suffices to promote speech sound acquisition. The current dissertation aims at contributing to answering this research question by: (1) Conducting a meta-analysis on a systematically-reviewed body of literature related to the use of complex and/or simple stimuli for the treatment of children with speech sound disorders (Study 1); (2) Comparing the trajectory of development of complex and simple speech sounds in typically developing children and those with speech sound disorders using Maximum Entropy Modeling (Study 2); (3) Comparing the efficacy of training with complex vs. simple speech stimuli in an artificial language training paradigm in adults (Study 3); and (4) Evaluating the efficacy of complex vs. simple speech stimuli in a speech therapy program in children with speech sound disorders (Study 4).

The complexity perspective has primarily emerged from the principles of generative phonology, natural phonology and optimality theory, which propose the existence of natural and innate mechanisms responsible for the acquisition of speech sounds in children. These mechanisms are viewed as *distinctive features* in generative phonology (Chomsky, 1959), *phonological processes* in natural phonology (Donegan & Stampe, 1979; Stampe, 1979), and *universal constraints* in optimality theory (OT; Prince & Smolensky, 1993, 2004). On the other hand, the traditional theories, including behaviorist, connectionist and dynamic system theories, assert that exposure to simple input before complex input rather than exposure to complex structures directly is needed for acquisition of speech and language to take place in a step-by-step manner.

1.1 Complexity in phonology

Phonological complexity can be measured in terms of *markedness*. Trubetzkoy (1969) introduced the term *markedness* to specify a comparison between elements of a phonological class (e.g., place and manner of articulation in consonants). Basically, there exists a *marked/unmarked* dichotomy where those elements that are more generic, natural, simpler and common are considered unmarked while those that are more specific, less natural and common, and more complex are considered marked. The degree of markedness of the elements governs the implicational hierarchy, both in linguistic typology and in acquisition. As a result, the presence of a more marked sound implies the presence of the corresponding lesser marked sound. For example, the presence of voiced plosives (/b/,/d/,/g/) in a language imply the presence of lesser marked voiceless plosives (/p/,/t/,/k/). Conversely, the presence of voiceless plosives does not imply the presence of more marked voiced plosives in a phonological inventory. In order to further understand the implicational relationship due to markedness hierarchy, consider the comparison of syllable structure in Hawaiian and English. In English, the presence of complex onsets (more marked) ensures the presence of CV syllables (less marked) while the presence of CV syllables in Hawaiian does not imply the presence of complex onsets (Elbert & Pukui, 1979). During the acquisition of speech sounds, the phonological inventory of a child contains more unmarked structures (e.g. plosives rather than fricatives) than marked structures (e.g. clusters as compared to simple consonants), chiefly because of the tendency of children to simplify complex sounds (marked) to simpler ones (unmarked).

1.2 Traditional theories

Traditional theories of speech sound development suggest that exposure to simple (unmarked/stimulable) input first followed by gradual increase in complexity is the key to acquisition (Elman, 1993). These traditional theories include behaviorist theories (Skinner, 1957), scaffolding theories (Piaget, 1962; Vygotsky, 1962), dynamic systems theory (De Bot, Lowie, & Verspoor, 2007; Rvachew & Bernhardt, 2010) and the connectionist models of language acquisition (Elman, 1993).

Behaviorism (Skinner, 1957; Watson, 1913), originally, has been concerned with observable stimulus-response behaviors, and suggests that learning of a behavior happens through interaction with the environment. The mainstay of the behaviorist theories, in the context of speech acquisition, is that the most easily discriminable sounds are learned first (Olmsted, 1971) mainly via imitation, in the presence of feedback and/or reinforcement. However, the behaviorist approach to speech acquisition in children has faced four key criticisms (Chomsky, 1959): (1) If the children have to depend on a stimulus-response-reinforcement relationship then the acquisition of speech cannot take place as quickly as it usually does; (2) Acquisition of speech and language is too complex to be explained solely on the basis of reinforcement; (3) The stimulus-response-reinforcement relationship does not justify the U-shaped developments in learning; (4) Acquisition of speech and language is not reliant on negative evidence or explicit corrective feedback.

Developmental theorists (Piaget, 1962; Vygotsky, 1962) believed that communication with others, particularly with adults, plays an important role in shaping a child's language. Vygotsky (1962) explains the presence of the zone of proximal development when children interact with adults. This zone is described as the "distance between the child's actual developmental level determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance." This adult guidance, referred to as *scaffolding* (Bruner, 1978), is known to further the development of language in a child. Scaffolding can be the most effective when the adult manages to understand and begins offering input at the developmental level of the child so that the child is comfortable enough to use their guidance. More specifically, scaffolding consists of building concepts in a hierarchical manner beginning with simpler ones.

Connectionist theories, in opposition to learnability theory that assumes both the learning device and input to be static, suggests that networks reconfigure dynamically across time so as to facilitate learning (Ash, 1989; Fahlman & Labiere, 1990; Shultz & Schmidt, 1991). Studies from computational modeling (Elman, 1993) report that starting with simpler structures is more advantageous than starting with complex structures. Elman (1993) compared the outcome of training of networks with complex sentences versus training with simple sentences. Complexity was defined on the basis of types of relative clauses, number agreement, and verb argument structure. It was found that the networks failed to learn when they were trained using complex material while they succeeded only when simple material was processed. Based on these findings, Elman (1993) suggested that training succeeds only when the networks begin with simple syntactic structures, and that there is a unique interaction of the course of maturation and language acquisition that paves the way for the development of complex forms. A gradual increase in the level of complexity can ensure more efficient outcomes than dealing with adult-like forms directly (Plunkett & Marchman, 1993).

Recently, there have been studies (De Bot et al., 2007; Rvachew & Bernhardt, 2010) that have applied dynamic systems theory to speech sound acquisition which is a modern iteration of the empiricist perspective that accounts for speech and language acquisition without relying on a competence-performance distinction (Bates et al., 1998; MacWhinney, 1999; Thelen & Bates, 2003). The main principle of this theory is that new behaviors emerge from complex interactions that take place among multiple developmental domains tied to task demands and environmental support. Dynamic systems theory proposes that it is due to interaction of the underlying components, and there is an emergence of continuities and discontinuities that leads to development of a new behavior. For development, the stability of the subcomponents has been considered to play a pivotal role. Unlike complexity theories, dynamic systems theories postulate that it is not necessary to set a parameter (for example, markedness hierarchy) for the development of a new class of speech sounds. Instead, “the same components that create stability may also be involved in shifting the system discontinuously to some other stable configuration” (Fogel & Thelen, 1987). In the context of speech sound development, stimulability of the simple sounds is needed first, followed by the steady acquisition of the difficult ones (Bernhardt, 1992; Rvachew & Bernhardt, 2010). For example, in order to teach clusters (more marked) to a child, stimulability of stops (less marked) is needed. Additionally, similar to the behaviorist theories, dynamic systems theory also emphasizes the importance of feedback and reinforcement in building concepts from most simple to most complex in increasing gradation of complexity (Rvachew & Bernhardt, 2010).

1.3 Complexity theories

Complexity theories in phonology are linguistic-based theories compatible with the basics of universal grammar, including generative phonology (Chomsky, 1959), natural phonology (Stampe, 1979) and optimality theory (Prince & Smolensky, 1993). Generative phonology (Chomsky & Halle, 1968) proposes the presence of a set of phonological rules that map the underlying representations onto surface pronunciations. Similarly, the natural phonology model (Stampe, 1979) advocates the universality of natural phonological processes (or patterns) that act on the underlying forms in children to bring out surface representations different from those of adults. These natural phonological processes are innate rules applied systematically to speech production until children learn to suppress them. Though these theories of phonological acquisition laid a solid foundation for the concept of universal grammar, they had their limitations. One of the limitations is that these theories propose that language requires several structurally different rules that govern synergistically to converge into a common end of phonological development, also popularly known as the 'conspiracy' problem (Kiparsky, 1976; Kisseberth, 1970). Another persistent problem is that these theories propose that young children's phonologies have such rules that cannot be learned by children from the primary linguistic data to which they are exposed (Donegan & Stampe, 1979). This problem is also observed in second-language acquisition (Broselow, Chen, & Wang, 1998; Eckman, 1981). The optimality theory (OT), on the other hand, overcomes these shortcomings and supports the concept of universality across languages, suggesting that language-specific rules are not sufficient to account for acquisition and that there must be a set of constraints that are universal to all languages. OT suggests that these universal constraints play an essential role in accounting for the effect of phonological processes.

Broadly, these constraints are of two types – *markedness* and *faithfulness*. These markedness and faithfulness OT constraints align themselves in a particular hierarchical ordering to bring about surface representations based on a set of underlying representations (i.e., lexicon). Markedness constraints evaluate the surface representations and penalizes them for certain configurations. For example, *VOI is a markedness constraint that penalizes voicing, i.e. it makes sure that the output does not have a voicing feature. On the contrary, faithfulness constraints act both on surface and underlying representations and ensure that the input and output are identical with no changes. For example, MAX avoids deletion to ensure that both the underlying and surface forms are identical. Despite these constraints being universal, their ordering differs between languages and language learners. Basically, OT accounts for phonological acquisition by depicting input-driven changes in the ordering of the OT constraints. In the initial state, markedness constraints always rank higher than the faithfulness constraints. It is the exposure to complex input that triggers the demotion of markedness constraints below the faithfulness constraints in the hierarchical ranking of constraints. As a result, unlocking of structures with lesser or equivalent markedness occurs that necessitates acquisition. In other words, exposure to complex input leads to unlocking of structures that rank lower or equal in the markedness hierarchy. This is mainly because marked or more complex structures expose a child to surface forms that cannot yet be generated by their internal grammar, triggering the improvement of other structures with an equivalent or lesser complexity leading to an overall change in their language system. In comparison, with exposure to simple input alone, faithfulness constraints always rank higher than the markedness constraints with no constraint demotion as a result of which speech sound acquisition does not take place (see Figure 1 for an illustration). For example, consider the hierarchy of constraints *ComplexCoda >> *Coda that means if there is a presence of a [CVCC] in a phonological inventory then [CVC] is implied. Conversely, it does not guarantee the presence of [CVCC] when [CVC] is present. This notion is in agreement with generative phonology where it is believed that exposure to positive evidence leads to unlocking of the acquisition of innate principles of linguistic organization at several levels leading to language acquisition.

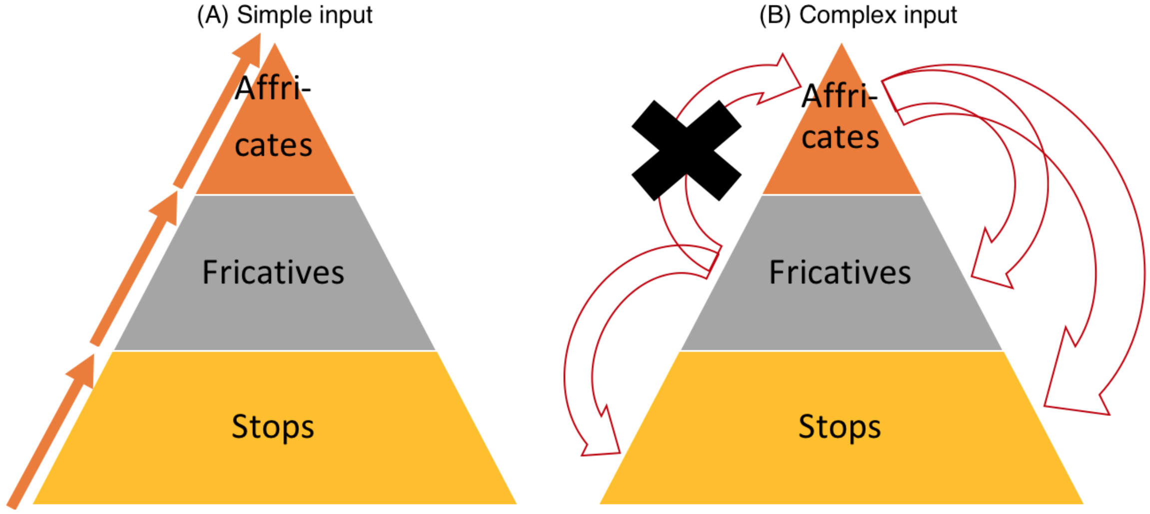

Figure 1. Comparison of the course of speech sound development via exposure to (A) Simple input vs. (B) Complex input. (A): Speech sound development takes place with exposure to stops followed by fricatives followed by affricates; (B): Exposure to more marked or more complex speech sound leads to generalization to lesser marked speech sounds, i.e. exposure to affricates generalizes to both fricatives and stops while exposure to fricatives only generalizes to stops but not affricates.

OT sets up a dichotomy between the *operational component* and *constraint component.* The operational component is called GEN and it generates all the possible candidate surface forms for a given underlying form. The constraint component known as EVAL selects one of these candidate surface forms to be the actual output of the grammar. It is believed that "if phonology is the computational link between the lexicon and phonetic form, then markedness acts as the advocate of the phonetic interface, faithfulness as the agent of the lexical interface" (Prince & Smolensky, 1993). Based on the demands of these phonetic and lexical modules, the constraints compete with each other to bring out certain rankings. Further, the constraint rankings may also differ within a language at least when comparing typically developing children and those with phonological disorders (Dinnsen, 2008). In a child acquiring language, markedness constraints outrank the faithfulness constraints in the initial state (Smolensky, 1996) which get demoted below faithfulness constraints with exposure to complex but not simple input. In order to understand and gauge complexity in phonology, constraint rankings as proposed in OT can provide a suitable framework (Dinnsen, 2008).

A recurrent pattern in child language data is that children's output is considerably less marked or less complex as compared to adult target output forms. Hence, a starting point in most phonological acquisition research has been the assumption that typically developing children begin with markedness constraints outranking faithfulness constraints. Through the course of development, complexity in children's input leads to a re-ranking of constraints causing faithfulness constraints to outweigh the markedness constraints by either promotion of faithfulness constraints (Bernhardt & Sternberger, 1998; Gnanadesikan, 2004; Stemberger & Bernhardt, 1997) and/or demotion of markedness constraints (Gnanadesikan, 2004).

While there is evidence (Bernhardt & Sternberger, 1998; Boersma, 1997; Boersma & Hayes, 2001; Gnanadesikan, 2004; Stemberger & Bernhardt, 1997; Tesar & Smolensky, 1998) looking at the OT constraints and rankings via linguistic analysis, there are also studies that have looked at the nature and complexity of constraints empirically. One way of establishing the psychological reality of the OT constraint rankings, which is reminiscent of complexity, is via their experimental manipulation in a training paradigm in children with phonological disorders (Barlow & Gierut, 1999). Motivation of this treatment approach stems from the OT analyses conducted by Gierut (2008) on the data of Lleó & Prinz (1996) that reported cross-sectional and cross-linguistic evidence of the emergence of consonant clusters in typically developing toddlers (0; 9 to 2; 2 years; months) learning Spanish or German as their native language. Their findings revealed that markedness constraints are the ones that outweigh faithfulness constraints initially in the development. However, as a child grows, faithfulness constraints start outweighing the markedness constraints, or in other words, the child's phonological system becomes increasingly complex with age. Gierut (2008) reinterpreted their data in three stages of development:

Stage 1: *COMPLEX>>FAITH

The markedness constraint *COMPLEX penalizes branching structure in the onset while the faithfulness constraint FAITH penalizes deviations from the underlying form in the output. At this stage, children cannot produce consonant clusters and affricates properly.

Stage 2: *COMPLEXONSET>>FAITH>>*COMPLEXSEGMENT

As development takes place, *COMPLEX explodes into *COMPLEXONSET which prohibits any complex structure in the syllable initial position, such as cluster, ranking higher than the faithfulness constraint FAITH and *COMPLEXSEGMENT, a markedness constraint that restricts the use of affricates. Since FAITH is ranked higher than *COMPLEXSEGMENT, the child is able to produce affricates successfully but not a cluster as FAITH still ranks lower than *COMPLEXONSET.

Stage 3: FAITH>>*COMPLEXONSET>>*COMPLEXSEGMENT

For acquisition of clusters, *COMPLEXONSET will be demoted below FAITH but it is still ranked higher than *COMPLEXSEGMENT. At this stage, children can produce both consonant clusters and affricates.

Based on the above interpretation of the data, Gierut (2008) argues that if there is an absence of complex input to a child with phonology which is similar to that represented in Stage 1, there might be no markedness constraint demotion, leading to stalling of the acquisition of speech sounds. Extending this interpretation to treatment of speech sound disorders, Gierut explains that if only affricates are stimulated in therapy then the children's phonological development may stall at Stage 2 where *COMPLEXONSET is still ranked higher than FAITH, thus creating problems for onset clusters to be acquired. On the other hand, if children are stimulated with more marked structures (consonant clusters) during the early stages, their phonology will reach Stage 3 where, because of the constraint re-ranking, there will be automatic improvement in clusters followed by generalization to affricates. In other words, exposure to more marked onset clusters implies less marked affricates while exposure to less marked affricates does not imply more marked clusters.

1.4 Previous studies

1.4.1 Non-clinical studies

The studies that support the use of complex or simple input span different areas of scientific research including speech and language acquisition (Abbot-Smith & Behrens, 2006; Au, 1990; Diessel, 2004; Roeper & de Villiers, 1992), second-language learning (Eckman, Bell, & Nelson, 1988), and cognitive development (Kuhn, 1972; Piaget, 1962). Complexity has been found to facilitate syntactic and semantic acquisition in first-language learning (Roeper & de Villiers, 1992). For example, Au and colleagues (Au, 1990; Au & Laframboise, 1990;

Au & Markman, 1987) found that children learned color terms better when two novel colors were contrasted with each other as compared to contrast between one known and another unknown color. On the other hand, Abbot-Smith and Behrens (2006) reported that complex syntactic constructions could be acquired by children if they had already acquired the underlying components of new complex construction. For example, children can acquire the German passive easily because they can build up on other auxiliary constructions. Diessel (2004) showed that in order to acquire complement clauses, children from English-speaking homes use the main clause in a semantically-limited manner. For example, they use the clause "I think" as an adverbial first, before generalizing to different types of syntactic dependencies. Traditionally, it is believed that teaching simpler concepts first sets the stage for the development of difficult concepts in a scaffolding manner (Vygotsky, 1962). On the other hand, Eckman et al. (1982) reported that for teaching English to non-native speakers, teaching complex relative clauses leads to the greatest generalization across the concepts of similar and lower levels of complexity as compared to teaching simple concepts. Piaget's stages of development, in cognitive science, are ordered in a manner of increasing difficulty such that children learn simpler concepts first before going on to complex ones. On the other hand, Kuhn (1972) experimentally demonstrated that when children are given items from later Piagetian stages (more complex) then they show more generalization as compared to treatment with items from initial stages. Elman (1993), using an artificial neural network, found that "starting small" or starting with simpler structures is the key to enhanced acquisition of language. In comparison, Rohde and Plaut (1996), using a pseudo grammar in a computational framework, found that a system learns the most when exposed to complete grammar rather than exposing the grammar in stages. Further, Plaut (1996) investigated the effects of exposing an impaired computer-simulated lexical-semantic network to a complex versus simple structure. It was found that exposing the impaired network to complexities leads to enhanced learning.

1.4.2 Clinical studies

1.4.2.1 Traditional theories-based therapy

Generally, the traditional clinical approach, mainly based on traditional theories (behaviorist, scaffolding, connectionist and dynamic systems theories) of speech sound acquisition, postulates teaching simpler or stimulable sounds first, followed by the introduction of difficult sounds with successive improvements (Van Riper & Emerick, 1984; Winitz, 1969, 1975). Traditional speech therapy usually begins with testing the stimulability of the child followed by ear training or auditory bombardment with the most stimulable sounds first. Here the child listens to the model articulation of the treatment targets and then monitors his/her own articulation of speech sounds. Most of the therapy involves treating the subjects through a gradation of levels of difficulty starting from simpler sounds/word position/contexts to more difficult ones. Other traditional clinical approaches include the "cycles" approach (Hodson & Paden, 1991; Mota et al., 2007), minimal pair training (Blache & Parsons, 1980; Blache, Parsons, & Humphreys, 1981; Elbert, Rockman, & Saltzman, 1980; Ferrier & Davis, 1973), psycholinguistics (Pascoe, Stackhouse, & Wells, 2005), and the perceptual approach (Morrisette et al., 2003; Rvachew & Bernhardt, 2010; Rvachew & Nowak, 2001). In the *cycles* approach (Hodson & Paden, 1991), the therapist treats the errors in "cycles" that entails treating an error for some duration and not aiming at achieving complete mastery before moving to the next class of speech sounds. If the child needs more treatment for a particular speech sound, it can be "re-cycled" later until mastery is achieved. In a minimal pair training program (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973), children are taught to differentiate between the correct articulation (target) and their incorrect articulation. Further, recently, there are studies (Rvachew, 1994; Rvachew, Nowak, & Cloutier, 2004; Rvachew, Rafaat, & Martin, 1999) that suggest the use of auditory perceptual training along with other traditional clinical techniques to enhance improvement in articulation. Rvachew and colleagues, using an auditory perceptual training program such as Speech Assessment and Interactive Learning System (SAILS; Avaaz Innovations, 1995), have revealed significant results in speech sound therapy for children with speech sound disorders. Recent studies (C. J. Johnson, 2006; Rvachew, 2005) reveal that inclusion of SAILS in the traditional speech therapy program significantly enhances the phoneme perception and production abilities, although the total dosage of SAILS can vary from short (30 minutes; Rvachew et al., 1999) to medium (60 minutes; Rvachew, 1994) to long duration (160 minutes; Rvachew et al., 2004).

1.4.2.2 Complexity theories-based therapy

On the contrary, complexity approaches for the treatment of phonological disorders stem from universal grammar or the innateness perspective (McCarthy, 2007; Prince & Smolensky, 1993; Tesar & Smolensky, 1998; Wexler, 1982; Wexler & Culicover, 1980). Complexity plays a facilitative role in language acquisition, irrespective of the linguistic domain – phonology, semantics or syntax (Gierut, 2001). Complexity approaches (Baker & Williams, 2010; Gierut, 2001; Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) recommend the introduction of complex (marked) structures in the therapy that promote the development of both complex (marked) and simpler (unmarked) structures. This is chiefly because exposure to marked structures facilitates the demotion of markedness constraints below the faithfulness constraints leading to speech sound acquisition. More specifically, exposure to more marked structures implies structures with equivalent or lesser markedness.

Motivated by the findings from the observational data (Bernhardt & Sternberger, 1998; Boersma, 1997; Boersma & Hayes, 2001; Gnanadesikan, 2004; Stemberger & Bernhardt, 1997; Tesar & Smolensky, 1998), treatment-based studies (Dinnsen, 2008; Dinnsen & Elbert, 1984; Powell & Elbert, 1984) have been conducted that have exploited the hierarchical complexity, indicated by OT constraint rankings in the treatment of children with phonological disorders. Treatment-based studies stress the extent of benefits or generalization an input can bring about for the untreated aspects along with the treated aspects. Generalization is an indication of extensive changes induced by the therapy and may be a reflection of children's own conceptualization of the sounds followed by the treatment (Gierut, 1989). Generalization due to treatment could be limited to within the same class of sounds (within-class) or could extend to other classes of sounds (across-class). For example, treating affricates leading to generalization to stops is an example of an across-class generalization while treatment of affricates leading to improvement in untreated affricates is an example of within-class generalization. Dinnsen and Elbert (1984) compared two children who were treated with stops (less marked) with another two children who were treated with fricatives (more marked). They found that as fricatives and stops are in an implicational relationship with fricatives being more marked than stops, the children who were treated with fricatives improved with regard to fricatives and generalized to stops while the children who were treated with stops only improved with regard to stops but did not generalize to fricatives. Recently, Dinnsen (2008) reported results from four experiments where a subgroup of children was treated with more marked sounds (onset clusters) while the other subgroup was treated with less marked sounds (affricates). They found that children who were treated with onset clusters improved with regard to onset clusters and generalized to affricates while the subjects that were treated with affricates improved only with regard to affricates but did not generalize to onset clusters.

1.5 The current dissertation

There is evidence, from both non-clinical and treatment-based studies, favoring the importance of complex input first (Au, 1990; Au & Laframboise, 1990; Au & Markman, 1987; Barlow & Gierut, 1999; Dinnsen & Elbert, 1984; Gierut et al., 1987, 1996; Morrisette et al., 2003; Plaut, 1996; Powell et al., 1991; Roeper & de Villiers, 1992; Rhode & Plaut, 1996; Tyler & Figurski, 1994) as well as there being studies that argue for the role of exposure to simple input before complex input (Abbot-Smith & Behrens, 2006; Blache & Parsons, 1980; Blache et al., 1981; Diessel, 2004; Elbert et al., 1980; Elman, 1993; Ferrier & Davis, 1973; Van Riper & Emerick, 1984; Winitz, 1969, 1975) in relation to speech sound acquisition. However, there is no clear consensus on whether it is the exposure to complex input first or simple input first that is instrumental in speech sound acquisition. One way to evaluate this is by comparing the effect of complex and simple input in a treatment paradigm. Evident from the literature, most of the previous treatment-based studies have been conducted on small subject samples from English-speaking homes, and do not consider the phonological system as a whole to determine the choice of the therapy technique. In addition, there is a considerable variability in the magnitude of effects, speech stimuli used, and the number of therapy sessions involved which makes it difficult to understand which approach is more efficacious than the other (see Table 1 for details).

Table 1. Summary of limitations of the previous studies, and the studies conducted to address them in the current dissertation

Limitations of the previous studies	**Solution**	**Addressed in the dissertation**
Variability in the magnitude of effects	To conduct a study that combines the data from the previous studies to obtain conclusive results on the efficacy of complex vs. simple speech stimuli	Chapter 2 (Meta-analysis of the findings from the previous studies on the use of complex and/or simple speech stimuli in therapy)
Variability in the sample sizes		
Variability in the number of sessions		
Did not analyze the phonological system as a whole to confirm whether speech sound disorders are a ‘delay’ or ‘deviance’ as compared to typically developing children	To analyze and compare the phonological profiles of typically developing children and those with speech sound disorders, using computational modeling methods	Chapter 3 (Comparison of development of phonological inventory of typically developing children and those with speech sound disorders using Maximum Entropy Modeling)
Traditional Optimality Theory does not account for free variations, i.e. one input can be realized as more than one grammatical form		
Disadvantages of single subject designs	To compare the effect of complex vs. simple speech stimuli in a two-group	Chapter 4 (Comparison of training with complex vs. simple stimuli using
Lack of a comprehensive		

study	randomized controlled design training study	artificial language training in adults)
Generalizability of the previous case reports, mostly from children from English-speaking homes, not known	To conduct a therapy study in a language with a different phonological inventory than English	Chapter 5 (Evidence from complex and simple speech therapy in children from Cantonese-speaking homes)

In light of the above shortcomings from the previous studies to be reviewed in the respective chapters of the current dissertation, there is a need for a systematic analytical review of literature that could combine the previous findings to bring out more conclusive reports on the efficacy of complex vs. simple stimuli. Thus, in the current dissertation, a meta-analysis of the systematically reviewed literature was conducted to extract and compare the effect sizes of the findings from the studies that dealt with complex and/or simple speech stimuli for therapy of children with speech sound disorders (Chapter 2). Meta-analysis is considered as an important avenue in consolidating and synthesizing research evidence (Collins & Fauser, 2005). However, meta-analyses are affected by the quality of studies that are included in it. As most of the previous studies that examined the effect of complex and/or simple therapy have employed single subject designs, known to be affected by lack of stable baselines, difficulty in determining the intervals between the probes, and variability across subjects (Diedrich, 1989; Rvachew & Nowak, 2001), there is also a need to supplement the current meta-analysis with experimental studies that could overcome these limitations.

Further, the assumption behind the use of a complexity approach for treatment is that children with phonological disorders have a similar (but delayed) trajectory of development of speech sounds as compared to typically developing children (Gierut, 2008). These findings stem from comparing the phonological patterns of children with phonological disorders with the age-appropriate normative data of acquisition. However, the previous studies did not consider comparing the phonological system of typically developing children and those with speech sound disorders, as a whole. Examining the whole phonological system can provide hints about whether a phonological disorder is suggestive of a 'delay' or a 'deviance' that is needed to guide the choice of the input to be used in therapy. In addition, the previous therapeutic case studies have mostly used traditional OT to account for the development of speech sounds. However, traditional OT does not allow free variations (i.e. where a single input can have multiple output grammatical forms) (Anttila, 1997), which is a characteristic of a speech sound disorder. In order to overcome these limitations, in the current dissertation, data from typically developing children and those with phonological disorders were analyzed using the maximum entropy modeling technique that takes into account the whole phonological system and accounts for free variations (Chapter 3).

Most of the previous therapeutic studies investigating the effect of complex vs. simple stimuli have been case reports conducted using single subject designs, and exhibit variability in the speech stimuli used, number of subjects, and the outcome measures studied. As a result, there is a need for a comprehensive experimental study that could settle the debate regarding whether it is complex stimuli or simple stimuli that induce maximum changes following training. Thus, a study with a two-group randomized controlled design was conducted as a part of the current dissertation to compare the efficacy of complex vs. simple stimuli in Cantonese-speaking adults, using artificial language training (Chapter 4). As children generally show better plasticity in response to speech training, as compared to adults, findings from a training study conducted on adults would be generalizable to children. In addition, as speech training-induced changes are neurally represented well (Kraus et al., 1995; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993; Tremblay, Kraus, Carrell, & McGee, 1997), and are apparent neurally even before being visible in the behavior (Tremblay, Kraus, & McGee, 1998), a neural investigation was considered to supplement the investigation of training-induced changes. Further, by examining the training-induced generalization, one could investigate the neurophysiological reality of markedness hierarchy. If the neurophysiological changes following complex training extend to both complex and simple stimuli, and simple training leads to changes in simple stimuli only, one can confirm the role of markedness hierarchy in necessitating speech sound development in a rule-governed manner. Although this study can overcome the methodological limitations posed by the previous studies, mainly due to the heterogeneity of the subjects, and simple research designs, this study was conducted on adults (with no speech and language problems) and not on children with speech sound disorders.

In order to examine the effects of complex and simple stimuli on children with speech sound disorders, another study was included in the current dissertation (Chapter 5). There are very few case reports (e.g., Dinnsen & Elbert, 1984; Powell & Elbert, 1984; Dinnsen, 2008) that have compared the two lines of treatment – complexity approach and traditional clinical approach. Further, most of the previous case reports have been conducted on children from English-speaking homes and reports from other languages are lacking. The English language has a fairly marked phonological inventory in terms of the types and number of speech sounds. In order to further shed light on the comparison of efficacy of the two lines of treatment, and to broaden the existing empirical base, conducting a study in a language with a relatively simple syllable structure is needed. Thus, in the current dissertation, a study was included that compared the complexity and traditional clinical approach in children with speech sound disorders from Cantonese-speaking homes.

With the combination of these four studies in the current dissertation, a converging answer was sought on whether or not it is complex input first or simple input first that is needed to drive speech sound acquisition. The details of the four studies are as follows:

1. **Meta-analysis of the Literature (Chapter 2):** Findings from the previous treatment-based studies (N = 15) on children with speech sound disorders were further analyzed to understand whether complex input or simple input leads to more improvement in correct production of speech sounds.
2. **Investigation of trajectory of development of speech sounds (Chapter 3):** Speech production data from 61 3-6 year old typically developing children and those with speech sound disorders were analyzed using a Maximum Entropy Modeling approach to understand and compare the trajectory of development of complex and simple sounds across these two groups. The findings from this study would further inform about the usefulness of complex and simple input in speech sound development.
3. **Comparison of the effect of complex vs. simple input on non-native adults (Chapter 4):** Adult native speakers of Cantonese who were trained with complex input (n = 48) were compared with those who were trained with simple input (n = 48) in an artificial language learning paradigm, to examine the extent of behavioral and neural changes following the training.
4. **Comparison of the effect of complex vs. simple input on children with speech sound disorders (Chapter 5):** Using a speech therapy paradigm, children with

speech sound disorders (N = 5) were treated with complex input or simple input in order to understand whether it is complex input or simple input that promotes maximum improvement in speech sound articulation.

Chapter 2

Complexity drives improvement for speech-sound therapy: Evidence from a meta-analysis

2.1 Introduction

Speech sound acquisition is fundamental to spoken language and is a subject of theoretical debates. A long-standing question that remains unresolved is whether speech sound development is driven by complex or by simple input. The traditional perspective (e.g., behaviorist theories, connectionist view, dynamic systems theory) proposes that starting with simple input is more important for speech sound acquisition while complexity-based perspective suggests that starting with complex input (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) facilitates speech sound acquisition. To further contribute towards answering the question of whether complex or simple input facilitates speech sound development, in the current study, we reviewed treatment-based studies grounded on complexity and traditional perspectives, and conducted a meta-analysis on their findings. Treatment-based studies provide us with an excellent opportunity to experimentally investigate the psychological reality of theories by selectively manipulating the treatment variables (Barlow & Gierut, 1999) to observe effects on atypical phonological patterns in population with speech sound disorders (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973).

Complexity of input could range from complexity due to linguistic factors, psycholinguistic structure, articulatory-phonetic factors, and conventional clinical factors (Gierut, 2001). Linguistic complexity, more specifically, phonological complexity, stems from universal grammar or innateness perspective (McCarthy, 2007; Prince & Smolensky, 1993; Tesar &

Smolensky, 1998; Wexler, 1982; Wexler & Culicover, 1980). *Complex theories* support that the introduction of more complex (more marked) structures in the therapy promotes the development of both complex (more marked) and simpler (less marked) structures. This is mainly because marked or more complex structures expose a child to surface forms that cannot yet be generated by their internal grammar, triggering the improvement of other structures with an equivalent or lesser complexity leading to an overall change in their language system (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994). Psycholinguistic complexity is based on the characteristics of words that affect word recognition in perception and production. For example, high frequency words are known to be more complex at a sublexical level as compared to words with low frequency. As a result, use of high frequency leads to greater generalization and change in the sound system than the words with low frequency (Gierut, Morrisette, & Champion, 1999). Articulatory-phonetic complexity refers to complexity of speech sounds based on the ease of pronunciation and perception. For example, non-stimulable sounds could be defined as more complex as compared to stimulable sounds. Treatment with non-stimulable sounds leads to more generalization to both stimulable and non-stimulable sounds while treatment with stimulable sounds only generalizes to treated stimulable sounds but not non-stimulable sounds (Powell et al., 1991). Complexity due to conventional clinical factors includes complexity due to clinical aspects, methodological strategies, and/or techniques. For example, a sound which is a consistent error is a more complex input than a sound which is an inconsistent manner, a sound that is later-acquired is more complex than an early-acquired sound, and pairing two new sounds in a minimal pair becomes harder to learn than pairing a new sound with an old sound. Gierut (2001) found that by using stimuli that are more complex, as defined above, one can achieve better system-wide generalization as compared to using simple stimuli.

On the other hand, the traditional perspective based on behaviorist, connectionist and dynamic system theories assert the "simple-first" principle according to which, the acquisition of speech sounds is mainly an outcome of beginning with simpler (unmarked/stimulable) speech sounds with a step-by-step increase in complexity (Elman, 1993). These traditional theories, hereafter called *simple theories* include behaviorist theories, dynamic systems theory and the connectionist view towards language acquisition (Elman, 1993). Behaviorism, from its inception (Skinner, 1957; Watson, 1913) has been focused on describing overt and observable behaviors. In speech sound acquisition, behaviorist theories focus on the environmental factors (stimuli) that could predict overt verbal behaviors (responses). The mainstay of behaviorist theories of speech and language acquisition is that the sounds that are simple or easy to discriminate are learned first (Olmsted, 1971) mainly via imitation.

Computational modelling studies based on connectionist theories (Elman, 1993) have provided evidence that starting with simpler structures is more beneficial than starting with complex structures. Elman (1993) suggests that the acquisition of language and the course of maturation interact in such a way that having simple input in the initial maturational development sets the stage for development of complex structures. Gradually increasing complexity over time is more beneficial to language acquisition rather than dealing with the complex adult-like forms directly (Plunkett & Marchman, 1993). While a typical assumption of learnability theory is that both the (innate) learning device and training input are static (Elman, 1993), the connectionist view suggests that the networks are not static and they reconfigure dynamically across time to facilitate learning (Ash, 1989; Fahlman & Labiere, 1990; Shultz & Schmidt, 1991). Recently, the dynamic systems theory has been applied to speech acquisition (De Bot et al., 2007; Rvachew & Bernhardt, 2010) that proposes that the development of a given behavior occurs from the continuities and discontinuities that emerge by the interaction of underlying components. For development to take place, stability of the subcomponents is of paramount importance. In the context of speech sound acquisition, in order to learn difficult speech sounds, stimulability of simpler sounds is needed first (Bernhardt, 1992; Rvachew & Bernhardt, 2010). For example, if a child is to learn clusters (more marked), then stimulability of plosives (less marked) is required. In a similar way to behaviorist theories, dynamic systems theory emphasizes the importance of feedback and reinforcement in order to strengthen the correct articulation of simpler sounds to promote the development of complex sounds (Rvachew & Bernhardt, 2010).

2.1.1 Simple theories-based therapy

The traditional-clinical or *simple therapy* approach may range from the "cycles" approach (Hodson & Paden, 1991; Mota et al., 2007) to minimal pair training (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973) to psycholinguistic (Pascoe et al., 2005) to a perceptual approach (Morrisette et al., 2003; Rvachew & Bernhardt, 2010; Rvachew & Nowak, 2001). Traditional speech therapy usually begins with ear training or auditory bombardment where a child listens to the therapist's articulation of target sounds and then monitors his/her own speech sounds. For example, if a child shows an improper articulation of [s], the therapist starts the treatment with the sound [s] in isolation followed by syllables (e.g., [sa], [as], [asa]) followed by words, phrases, sentences and finally to the conversational speech. Next, the sounds in various contexts and various word-positions are worked on. Typically, the speech sounds are taught in word-initial positions first, followed by word-final and word-medial positions. Most of the therapy involves spanning through a hierarchy of difficulty levels starting from simpler sounds/word position/contexts to more difficult ones. Another form of traditional-clinical approach for treated phonological disorders is the *cycles* approach (Hodson & Paden, 1991), where auditory bombardment is accompanied with speech production starting with sounds that are most stimulable and easiest for the child. In this technique, the full range of errors, context and error patterns are identified first. Here, the therapist does not wait for the child to achieve mastery of a pattern of sounds before moving on to the next. Instead, treatment for various sound patterns is administered in cycles. If the child has not mastered a class of speech sounds, it can be "recycled" until the criterion for mastery is met. This approach exposes the child to dealing with a wide range of speech sounds in a simultaneous manner. Minimal pair training (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973) is another type of traditional-clinical approach in which a child is taught to differentiate between the target sound and the sound he/she produces instead. The treatment may consist of sounds in isolation or embedded in a word. For example, for training a child to differentiate between [f] and [s], a therapist may administer auditory minimal pair training with contrasts such as *fun-sun*, *fit-sit*, etc. The goal of this technique is to correct the children's articulation by instructing them to produce two distinct sounds, in order to signal two different meanings. Again, the therapy is focused on starting with easier/more stimulable sounds first. Recently, the use of perceptual training has been advocated along with other traditional-clinical techniques for better outcomes. Rvachew and colleagues have proposed that perceptual training of stimulable sounds first is a better option as compared to training unstimulable sounds, a notion supported by complexity-based approaches. Rvachew (1994) encourages the use of a perceptual training program such as Speech Assessment and Interactive Learning System (Avaaz Innovations, 1995). Rvachew (1994) studied 27 children aged 42 to 66 months with moderate to severe articulation difficulty. All their participants had articulation problems of [ʃ] during pretesting. During therapy with SAILS, they listened to a variety of naturally produced exemplars beginning with [ʃ] for several sessions that led to a significant improvement. Rvachew believes that this training activity could have led to improvement in the internal representation of phoneme /ʃ/ in their subjects by allowing them to monitor their accuracy of production and self-correct their errors. Rvachew et al. (1999) also included the SAILS program in their treatment of phonological disorders. With the inclusion of SAILS, improvement was observed for 80% of the targets, irrespective of their pre-treatment levels of speech perception and stimulability. Rvachew et al. (2004) used SAILS (16 once-weekly sessions) intervention in 34 children with moderate or severe speech sound disorders. Their experimental group received SAILS intervention, targeting a different phoneme each week, in word initial position during the first 8 weeks and in word final position in the last 8 weeks. The control group listened to computerized books and answered questions about the pictures. Improvements in standardized articulation scores and the percentage of consonants correct in conversation were significantly greater for the experimental group than the control group. Follow-up testing after a year revealed that 50% of children in their experimental group achieved normalized speech compared to 19% of children in their control group. Recent reviews on the above studies (C. J. Johnson, 2006; Rvachew, 2005) revealed that SAILS significantly boosts phoneme perception and production, although the total dosage of SAILS may vary from 30 minutes (Rvachew et al., 1999) to 60 minutes (Rvachew, 1994) to 160 minutes (Rvachew et al., 2004).

2.1.2 Complex theories-based therapy

A series of studies (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) have been conducted using complexity, defined by OT constraint ranking hierarchy, in the treatment of children with phonological disorders. Dinnsen and Elbert (1984) tested the prediction that treating more marked or complex structures leads to the development of less marked or less complex structures but not *vice versa* in treating children with phonological disorders with stops (less marked) and fricatives (more marked). Out of four children they studied, two children were provided with training with stops and the other two were provided training with fricatives. The children learning stops (less marked) showed an improvement only on stops while those who were treated on fricatives (more marked) improved on fricatives and generalized to stops. Their prediction that treatment of more marked or complex structure leads to generalization of simpler structures but not *vice versa*, turned out to be correct. Dinnsen (2008) reported findings from four experiments where 50% of the children from the experimental group were treated with more marked onset cluster while the other 50% were treated with less marked affricates in a multiple baseline experimental design. They found that treatment with marked or complex structures (onset clusters in this case) led to more generalization of marked and unmarked (less complex) structures as compared to treatment with unmarked structures (affricates) alone. Generalization could be an indication of the extensive changes in the phonological system developed by using complex stimuli. Children's generalization, both across- and within-class, may be a reflection of their own conceptualization of the sounds used in treatment (Gierut, 1989). The improvement following training may span categories and the extent of improvement will define the extent of reorganization of internal grammar of the child. In sum, generalization can give us a deep insight into the reorganization of the child's phonological system. While the aforementioned studies utilize linguistic complexity by using more marked structures in the therapy, there are studies (Gierut et al., 1987; Gierut, 1991; Gierut, 1992; Gierut, 1990; Williams, 2000) that use complexity defined by psycholinguistic, acoustic-phonetic, and methodological or technical factors. Gierut et al. (1987) compared the subjects who were trained with "most knowledge" speech sound stimuli with those who were trained with the "least knowledge" speech sound stimuli. They found that the subjects trained with “least knowledge” stimuli showed maximum generalization. Similarly, Gierut (1992) found that training with 2-new phonemes (complex) led to greater generalization than training with 1-new phoneme (simple). Powell et al. (1998) found that phonological training, involving a lot of conceptualization, led to more improvement as compared to simple motoric training. Gierut (1991) found that training with minimal pairs containing stimuli unknown (complex) to the subjects was more beneficial than training with homonymous minimal pairs (simple) with a new and an old sound. Gierut and Neumann (1992) found that training using non-homonymous pairs of sounds that are outside the grammar of the children led to more changes in the phonological system as compared to using homonymous sound pairs where one sound was in the child’s repertoire while the other was not. Williams (2000) compared the efficacy of a multiple opposition technique with a minimal pair technique and it was found that the use of multiple oppositions led to more changes in the phonological system as compared to using minimal pair, probably because of the increased difficulty by combination of multiple sub-tasks in training using multiple oppositions.

2.1.3 Motivation for the current study

So, there is evidence favoring complexity therapy (Barlow & Gierut, 1999; Dinnsen & Elbert, 1984; Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) as well as traditional simple therapy (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973; Van Riper & Emerick, 1984; Winitz, 1969, 1975) procedures. However, there is a considerable variability in the magnitude of effects across the studies that make it difficult to understand which approach is more efficacious than other. One way to compare the results from the studies is by conducting a meta-analysis in which the data are extracted, processed and plotted together to conduct a systematic review.

Previously, review studies (Baker & McLeod, 2011; Gierut, 1998; Law, Garrett, & Nye, 2003, 2004; Nelson, Nygren, Walker, & Panoscha, 2006) have discussed different techniques used in different time frames for the treatment of phonological disorders. However, these reviews were carried out with a pure clinical perspective to guide the speech language pathologists (SLPs) in their clinical practice and did not aim at addressing the theoretical questions on speech sound acquisition/development. In addition, with the proliferation of data in clinical research and the advent of studies considering evidence based practice frameworks, there is a constant need to revisit the empirical evidence in order to update inferences on the usefulness of approaches for the treatment of phonological disorders. Sommers, Logsdon, and Wright (1992) reviewed studies published between 1970 and 1990 from four journals. They provided an excellent review on the methodology of 63 studies by considering their research designs, participant criteria, rationale and descriptions of measurement procedures, the presence and absence of reliability data. Although their study provided useful information on the type and quality of studies during the period from 1970 to 1990, they did not compare different types of therapy procedures considered by these studies. Gierut (1998) advanced to examine the evidence from 64 studies conducted between 1980 and 1995 and reported that there are four main approaches towards phonological intervention that can be summed up as traditional intervention (Van Riper & Emerick, 1984), minimal pairs (Gierut, 1992; Weiner, 1981), cycles (Hodson & Paden, 1991; Mota et al., 2007) and Metaphon (Dean, Howell, Waters, & Reid, 1995). Additionally, Gierut also examined the issue of generalization to new untreated sounds following intervention and addressed the issue of relative efficiency of the techniques in intervention for phonological disorders. Quite recently, Baker and McLeod (2011) conducted a comprehensive review of studies from the last three decades. They reviewed 134 studies and discussed the results in terms of demographical and methodological characteristics and, approaches to target selection and intervention. The demographical and methodological characteristics they reviewed were source and date of publication, participants, service delivery, research designs, efficacy versus effectiveness studies and level of evidence. In their comprehensive narrative review, they revealed seven distinct approaches to phonological intervention consisting of the developmental approach (Rvachew, 1994, 2005, Rvachew et al., 2004, 1999), cycles approach (Hodson & Paden, 1991; Mota et al., 2007), nonlinear approach (Bernhardt, Stemberger, & Major, 2006), systemic approach (Williams, 2000, 2005), neuronetwork or whole language approach (Hoffman, 1990), psycholinguistic approach (Pascoe et al., 2005) and complexity approach (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994). The 134 identified studies were published in 28 journals with a major share in the American Speech-Language-Hearing Association (ASHA) journals (44%) followed by *Clinical Linguistics and Phonetics* (12.7%), the *International Journal of Language and Communication Disorders* (9%) and *Child Language Teaching and Therapy* (9%). Most studies (78%) had less than 20 participants with only seven studies (5.2%) with more than 50 participants. The participants in the studies included in their review ranged from 1;11 (years; months) through 10;5, with most being between 3;0 and 5;11. The authors also discussed about the methods of service delivery where it was found that the majority of intervention took place in a one-to-one format (78.7%) with some studies conducted as group settings (10.3%) or a combination of both individual and group sessions (7.4%). Although their study provides a comprehensive review of a multitude of approaches towards intervention with a deep discussion on demographic variables, but in a similar way to the previous reviews, it does not address the theoretical questions on mechanisms that drive phonological acquisition/development.

Comprehensive narrative reviews (e.g., Baker & McLeod, 2011; Gierut, 1998) have been criticized for their unsystematic selection of literature with a broad focus (Collins & Fauser, 2005). On the other hand, systematic reviews and meta-analyses have been advocated as being an avenue to consolidate and synthesize research evidence (Garrett & Thomas, 2006). According to Collins and Fauser (2005), meta-analysis can provide unbiased, rigorous and focused appraisal of methodologically well-defined studies on specific fields or questions. In the past 3 decades, there have been only two meta-analysis reviews (Law et al., 2003, 2004; Nelson et al., 2006) on the treatment of phonological disorders (Baker & McLeod, 2011). However, these reviews suffer from the following shortcomings: (1) *Less number of empirical studies included:* Law et al. (2003, 2004) have reviewed only 6 studies including 2 unpublished ones; (2) *Included studies only with randomized controlled trials (RCTs):* Law et al. (2003, 2004) and Nelson et al. (2006) have only included studies with RCTs. In the field of communication disorders, it is not always possible to implement RCTs because of the idiopathic nature of the disorders and heterogeneity in the affected population. Additionally, there are other factors such as living conditions, motivation, teacher and parental support that can affect the therapeutic outcome (Dodd, 2008).

Nonetheless, RCTs are considered the gold standard for evaluating clinical intervention across health service provision (Reilly, 2004). They are considered the highest level of evidence by ASHA (Robey, 2004) and the ("Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009)," 2009). RCTs have been widely used in the field of medicine for conducting clinical trials. In a RCT, patients are randomly allocated to the treatment and non-treatment groups and the outcome is compared by conducting a double-blind assessment where both the assessing clinician and the client are unaware of the type of treatment provided. RCT is considered a simple, straightforward way of evaluating efficacy of the intervention provided for a specifically diagnosed physiological condition. In the subfield of treatment of speech sound disorders, RCTs have been employed in a few studies

(Rvachew, 1994; Rvachew & Brosseau-Lapré, 2015; Rvachew et al., 2004) examining intervention via perceptual training. Rvachew (1994) conducted a RCT in 27 preschoolers to evaluate the effect of perception training on correct production of the sound /ʃ/. The children were randomly assigned to one of three treatment conditions in the study. The children in the experimental group learned to categories the correct and incorrect versions of the *shoe* with multi-talker adult and children recordings. Children in the second group learned categories *shoe* and *moo* with single-talker recording. Children in the control group learned to identify words like *Meat* and *Pete* that were unrelated to their articulation errors. They found that the groups treated with minimal pairs containing words with /ʃ/ improved on production /ʃ/ while the control group did not improve on the production of /ʃ/. Rvachew et al (2004) conducted a RCT with 34 preschoolers with moderate to severe phonological delays. The children were randomly allocated to experimental and control groups. The children in the experimental group were trained for phoneme perception while the control group listened to computerized books. They found that their experimental group significantly improved on phoneme perception and articulation accuracy, compared to the control group. Recently, Rvachew and Brosseau-Lapré (2015) conducted a RCT in 65 4-year-olds with developmental phonological disorder to compare the efficacy of four different approaches to phonological intervention. They found that the most effective strategy was to teach the parents to use the treatment approaches at home along with a congruent direct intervention program.

However, given the problems with the use of RCTs in the treatment of communication disorders (Dodd, 2008), much of the research (29.6%) on speech sound disorders conducted in the last three decades has resorted to the use of single-case experimental design (SCED) (Baker & McLeod, 2011). Thus, by only including studies consisting of RCTs, the previous reviews (Law et al., 2003, 2004; Nelson et al., 2006) have ignored a large body of treatment evidence (mostly with SCEDs). Though SCEDs have faced criticisms, mainly due to the lack of stable baselines, and difficulty in determining the time intervals between probes and variability across subjects (Diedrich, 1989; Rvachew & Nowak, 2001), nevertheless, they play an important role in treatment studies for at least three reasons: (1) SCEDs work well with a heterogeneous population. Children with phonological disorders often display phonological profiles which are different from one another, quantitatively and/or qualitatively. RCTs with two-group comparisons may not be the first choice for these profiles, as two-group comparisons assume homogeneous sampling; (2) As participants are evaluated at multiple time-points in the baseline as well as treatment conditions, each participant serves as his/her own experimental control. In addition, intervention with SCEDs is ethically better than the withholding of the control group from treatment (as in large N studies) in RCTs; (3) SCED is more relevant to clinical practice in communication disorders as it examines changes within a patient. In addition, SCED data from many subjects can be combined to form groups as well. Additionally, Gierut (2008) argues that data collected with multiple baseline single subject designs yield many more data points as compared to group-level study. So, given the advantages of SCEDs, the current meta-analysis was conducted on this extremely important but largely ignored volume of research about the treatment of phonological disorders.

The main goal of a treatment program for speech sound disorders is to rectify the problematic sounds and generalize to other untreated sounds in the phonological system. Changes in both treated and untreated sounds are considered as important indicators of treatment efficacy (Gierut, 1998). Most of the previous reviews have overlooked the aspect of generalization to untreated sounds which occur, resulting from treatment to the treated sounds. In the current review, we aimed to investigate the effects of treatment on both treated and untreated sounds, to understand the type of treatment approaches leading to generalization, which is an indicator of system-wide changes in phonological abilities leading to rapid phonological acquisition.

2.1.4 Current Study

To date, there is no clear consensus on what the most effective approach for is treating children with phonological disorders. At this point, we believe that there is a need for a systematic review of studies on this previously ignored but important literature on the treatment of phonological disorders using SCEDs, that can contribute to the long-standing debate on the two competing perspectives towards speech sound acquisition i.e. complex theories vs traditional simple theories. So as to achieve this quantitatively, we undertook to conduct a meta-analysis of the findings from previous intervention studies. Specifically, the current meta-analysis is aimed to address a systematic comparison between complex and simple therapy approaches for the treatment of phonological disorders. Along with measuring the outcome on treated sounds, we also looked at the generalization of treatment to other untreated sounds. As generalization to other untreated sounds reflects widespread changes in the phonological system, it forms an important measure of treatment efficacy (Gierut, 1998). The scores on the outcome measures of all the selected studies were converted to effect size (Cohen’s d) for the ease of calculation and comparison. We predicted that if the complexity therapy procedures led to a greater average effect size than the traditional simple therapy procedures, it would imply that complexity in linguistic structure contributes towards phonological development. On the contrary, if the traditional-clinical simple therapy approach led to a greater average effect size on both treated and untreated speech sounds as compared to complexity-based approaches, we can conclude that starting with simple input can promote better learning than linguistic complexity.

2.2 Method

2.2.1 Identification of studies

Before we carried out any searches, we developed inclusion criteria for studies based on study design, types of intervention, age of participants and outcomes (Table 2). The relevant literature was obtained by searching for studies in literature databases consisting of Google Scholar, Campbell Collaboration Social, Psychological, Education, and Criminological Trials register; Cochrane Database of Systematic Reviews; EMBASE; Psych INFO; and MEDLINE.

Table 2. Inclusion criteria for the studies to be included in the meta-analysis

Design
Participants treated in a Single Case Experimental Design (SCED) that includes single or multiple baselines AB, ABA designs. All other designs consisting of Randomized Controlled Trials, case studies, two-group comparisons were excluded
Types of intervention
Studies related to complexity-based approaches and traditional-clinical approaches were included
Participants
Preschoolers and school-age children diagnosed with articulation or phonological disorder
Outcomes
Post-therapy scores on phonology or articulation testing

The keywords mentioned below, or their combinations were used to search for the relevant literature: children, school, articulation, clinical, phonology, Optimality Theory, complexity, traditional, comparison, differential, treatment, minimal pair, cycles, perceptual, early/late-acquired, stimulable/non-stimulable, auditory and training. The inclusion criteria (Table 2) were applied in a series of six hierarchical steps starting with a broad search criterion in step 1 with 281 studies, narrowing it down to step 6 with 15 studies (Figure 2).

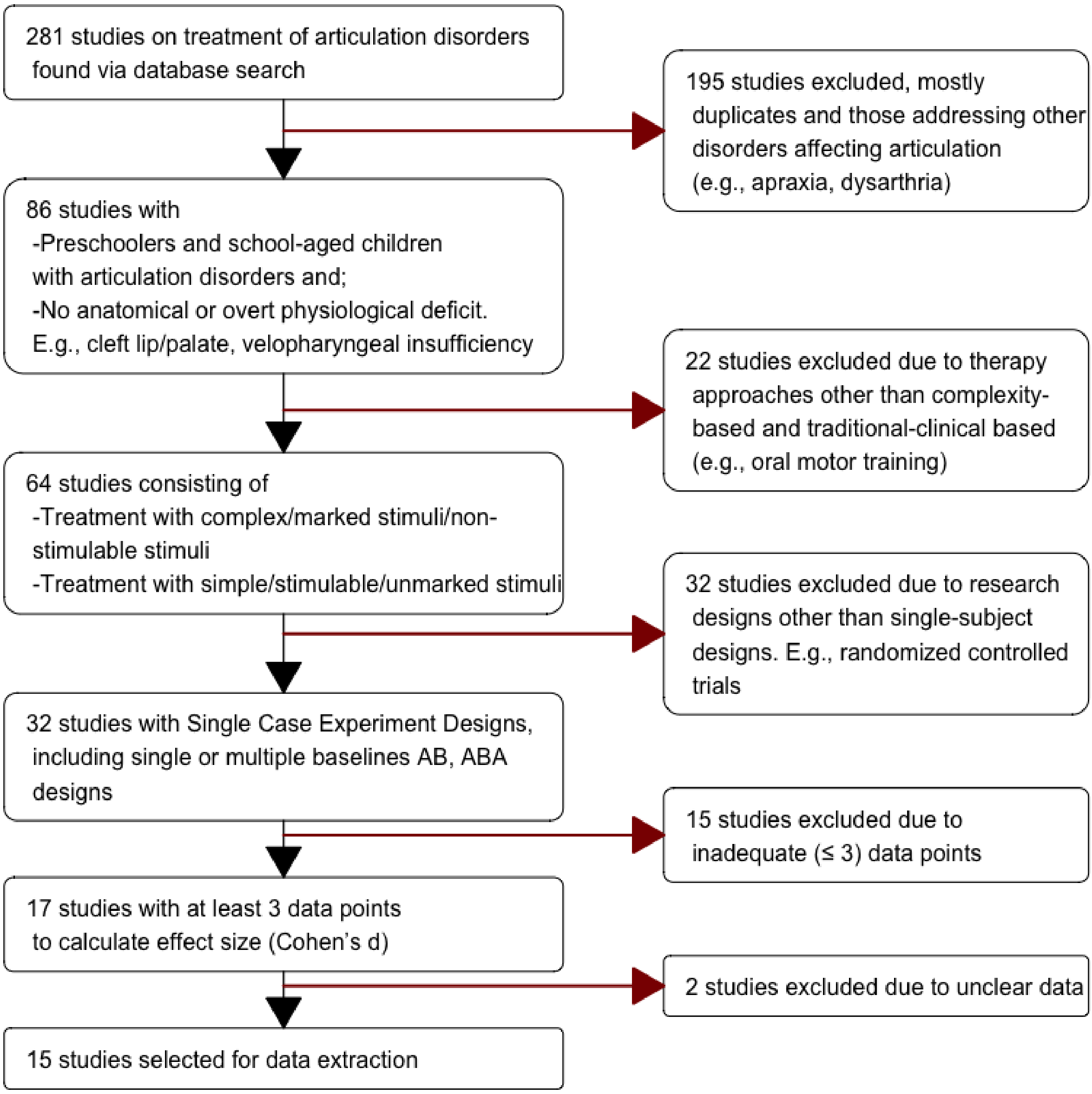

Figure 2. PRISMA chart showing the process of study identification for meta-analysis

2.2.2 Coding

Studies that met the inclusion criteria (Table 2) were coded for research design, participants, types of intervention and outcome. All the 15 selected studies were independently coded by the first author and the second rater. Agreement of ~ 87% was established between the coders and opinion from last author was sought for the disagreements. The second rater and the last authors were blinded to the quantitative results at the time the classification was made.

2.2.3 Participants

Studies with preschoolers and school-age participants were considered in this meta-analysis review. The participants from all these studies were native English speakers ranging from 3;5 to 5;6 years of age. They all had hearing abilities within normative limits and normal oral and speech motor abilities.

2.2.4 Interventions

As we are interested in reviewing studies that investigated the effect of complexity therapy and/or traditional simple therapy, we coded the studies accordingly. Some studies were given multiple codes as they had compared complexity therapy and simple therapy approach. The studies were also coded for their research designs, mode and total duration of service delivery.

2.2.5 Outcomes

So as to obtain homogeneity, for the purposes of meta-analysis, it was ensured that all studies focused on similar outcome measures. For example, scores on post-therapy measures. Outcomes of interventions for treated and untreated (whenever available) speech sounds were coded.

2.2.6 Extraction of data

In order to calculate the effect sizes, data were either extracted from the tables in the studies or they were retrieved from the graphs in the studies using a pencil and a ruler (Beeson & Robey, 2006). These data were converted to percentage values to further calculate the effect sizes.

2.2.7 Calculation of Effect size

Effect size (Cohen's d) was calculated following the recommendations from Beeson and Robey (2006). The data points were considered both for pre- and post-therapy. Usually Cohen's d is calculated as

$$d = (\bar{x}_{A2} - \bar{x}_{A1})/SD_{A1} \quad (1)$$

However, as a few studies had zero-variance values in the pre-therapy baseline, it was not possible to calculate the standard deviation (SD) for the pre-therapy condition. Instead, a pooled SD was derived by combining SDs of both pre- and post-therapy (Beeson & Robey, 2006). The effect size calculated using the pooled SD was calculated as d_2 (Busk & Serlin, 1992).

$$d2 = (\bar{x}_{A2} - \bar{x}_{A1})/SD\textit{pooled} \quad (2)$$

where A_2 is post-therapy evaluation and A_1 is pre-therapy evaluation.

Effect sizes were weighted for the number of observations in the pre- and post-therapy assessments. Further, effect sizes from each study were weighted for the number of subjects to obtain a *summary* (overall) effect size.

2.3 Results

Table 3 provides a summary of the studies selected for the current meta-analysis. As the current meta-analysis has placed emphasis on the comparison of the effect of complexity and traditional-clinical type of procedures, there were studies that dealt with one or both of these approaches. The therapy procedures were criterion-dependent (targeting 75-90%) and/or duration-dependent (≤20 sessions). Service delivery ranged from home- to school- to clinic-based therapy. Effect size was calculated as standardized mean difference (SMD) obtained by subtracting pretest means from post-test means relative to the variability observed in the non-treatment period (pre- and post-therapy). SMDs were used for plotting forest plots with confidence intervals on either side so that comparison across studies could be done in an efficient manner.

Table 3. Summary of studies coded for demographics, site of service delivery, study duration and research designs

Reference	Intervention Approaches	Research Design	Participant number and age (in parenthesis)	Site of service delivery	Study duration	Summary of findings	Type of complexity involved
(Williams, 1991)	Complexity approach	Multiple-baseline AB design	n = 9 (3;8 - 5;9)	Not clear	70% accuracy or maximum of 20 sessions	Found that the "least knowledge" (complex) sounds (clusters: /set/, /try/) led to improvement in 8 out of 9 subjects	Conventional -clinical
(Williams, 2000)	Complexity approach (Complex to Simple), Simple approach (Simple to Complex)	ABA	n = 1 (3;5)	Clinic	15 sessions	1.Multiple opposition treatment (complex paradigm) with /w/ against other sounds in minimal pairs led to improvement in both treated (/w/) and untreated sounds (/s/, /she) 2.Simple paradigm stimuli with /w/-only sounds led to improvement of /w/ but did not generalize to untreated sounds (/s/, /she/)	Psycholinguistic
(Powell & Elbert, 1984)	Complexity approach (Complex to Simple), Simple approach (Simple to Complex)	Multiple-baseline AB design	n = 6 (4;4-6;3)	Clinic	90% accuracy	1. Training stop liquid clusters (simple) improved treated stop liquid but did not generalize to fricative liquid (complex) 2. Training fricative liquid (complex) improved treated	Linguistic

						fricative liquid and generalized to untreated stop liquid (simple)	
(Gierut & Champion, 1999)	Complexity approach	Multiple-baseline ABA design	n = 2 (4;0-4;8)	Clinic	75% accuracy or maximum of 7 sessions	Investigated s-->θ-->f chain shift pattern and treated /s/ sound as it was on the end of the chain (most marked) and found significant improvement.	Linguistic
(Gierut et al., 1996)	Complexity approach (Complex to Simple), Simple approach (Simple to Complex)	Multiple-baseline AB design	n = 3 (3;7-5;6) n = 6 (3;5-5;6)	Not clear	75% accuracy of 2 consecutive sessions	1. Treatment of later-acquired (/r/, /s/, /θ/) sounds led to more changes when compared to treatment with early-acquired sounds (/k/, /g/) 2. Treatment of more marked sounds (/s/) generalized more to untreated lesser marked sounds (other fricatives, stops)	Linguistic
(Schmidt & Meyers, 1995)	Complexity approach (Complex to Simple), Simple approach (Simple to Complex)	Multiple-baseline AB design	n = 4	Clinic	19 sessions	1. Traditional Approach (Subjects 1 and 2): Treated with voiceless (simple) fricatives, affricate and measured effect on voiced along with voiceless fricatives and affricates (complex) /s, ʃ, tʃ/ 2.Complexity-based phonological-contrast approach (Subjects 3 and 4): Treated with English fricatives and	Linguistic

						affricates, voiceless first and voiced later	
(Gierut et al., 1987)	Complexity approach (Complex to Complex, Simple to Complex)	Multiple-baseline AB design	n = 6 (3;7-4;6)	Clinic	90% accuracy of two consecutive 30 minute sessions	1. The subjects 1, 2 and 3 were treated with aspects labelled "most" knowledge (simple stimuli) and subjects 4, 5 and 6 were treated with aspects labelled as "least" knowledge (complex stimuli). 2. Subjects treated with complex stimuli showed more improvement than those treated with simple stimuli	Conventional -clinical or Methodological type
(Powell et al., 1998)	Complexity approach, Simple approach	Multiple-baseline AB design	n = 6 (3;6-6;10)	Not clear	Maximum of 20 sessions	Overall, conceptual (phonological) training with /s/ (complex) led to more improvement as compared to treatment with simple motoric training of /s/	Conventional -clinical or Methodological type
(Gierut, 1992)	Complexity approach, Simple approach	Multiple-baseline AB design	n = 4 mean=3;10	Clinic	90% accuracy or maximum of 12 sessions	Investigated 2-new phoneme (complex) vs 1-new phoneme Strategy (simple) and found that 2-new phoneme strategy was more successful	Conventional -clinical or Methodological type
(Gierut, 1991)	Complexity approach, Simple	Multiple-baseline AB	n = 2 (4-5)	Home	75% accuracy of 2	Homonymous minimal pairs (simple) vs unknown set	Conventional -clinical or

	approach	design			consecutive sessions	(complex) strategy: Found that treatment with unknown set led to more improvement than homonymous pairs	Methodological type
(Gierut & Neumann, 1992)	Complexity approach, Simple approach	AB	n = 1 (4;8)	Clinic	75% accuracy of 2 consecutive sessions then 90% accuracy over 3 consecutive sessions	1. Treated for homonymous condition: /s, t/ 2. Treated for non-homonymous condition: /sh,Θ/ Found more improvement with homonymous (complex) than non-homonymous condition (simple)	Conventional -clinical or Methodological type
(Miccio & Ingrisano, 2000)	Complexity approach (Complex to Simple)	ABA	n = 1 (5;3)	School	90% accuracy of 3 consecutive sessions	Complex stimuli (/v/, /z/) led to improvement in treated complex sounds (/v/, /z/) and generalized to untreated simple speech sounds (/f/, /θ/, /s/)	Linguistic
(Gierut, 1990)	Complexity approach, Simple approach	ABA	n = 3 (4)	Clinic	75% accuracy of 2 consecutive sessions	Maximal opposition (simple; /g-m/) versus minimal opposition (complex; e.g. /s-t/,) compared. Maximal opposition led to greatest success	Psycholinguistic
(Rudolph & Wendt, 2014)	Traditional-clinical approach	Multiple baseline SSD	n = 3	Clinic	18 sessions	Traditional therapy using minimal pairs focused on led to improvement in the taught sounds (fricatives, liquids)	--
(Weiner, 1981)	Traditional-clinical approach	Multiple baseline SSD	n = 2 (4;4-4;10)	Clinic	3 sessions per week	Treated 2 subjects for final consonant deletion, stopping and fronting. Traditional	--

						therapy led to improvement in the taught sounds	

2.3.1 Analyses

The aims of the current study were to extract and analyze the data from the literature pertaining to the use of complexity-based and traditional-clinical techniques and thus, provide a quantitative comparison between these two major approaches for the treatment of speech sound disorders. The effectiveness of these approaches was compared on the treated as well as untreated speech sound categories. Out of the 15 studies (N = 59) that were selected, 9 studies dealt with both the procedures, 13 dealt with the complex approach and 11 dealt with the simple approach. Additionally, 6 studies looked at the effect of treatment using complex stimuli on untreated simple speech sounds and 4 studies looked at the effect of treatment using simple stimuli on untreated complex speech sounds (Table 4).

Table 4. Distribution of studies across the therapy approaches

Studies	Effect of Complexity-based approach on		Effect of Traditional-clinical approach on	
	Treated complex speech sounds (n=13)	Untreated simple speech sounds (n=6)	Untreated complex speech sounds (n=11)	Treated simple speech sounds (n=4)
(Williams, 1991)	+			
(Williams, 2000)	+	+	+	+
(Powell & Elbert, 1984)	+	+	+	+
(Gierut & Champion, 1999)	+			
(Gierut et al., 1996)	+	+		+
(Schmidt & Meyers, 1995)	+	+	+	+
(Gierut et al., 1987)	+	+	+	
(Powell et al., 1998)	+			+
(Gierut, 1992)	+			+
(Gierut, 1991)	+			+
(Gierut & Neumann, 1992)	+			+
(Miccio & Ingrisano, 2000)	+	+		
(Gierut, 1990)	+			+

(Rudolph & Wendt, 2014)				+
(Weiner, 1981)				+

With the data extracted from these selected studies (Table 3), forest plots were constructed to depict the effect sizes (Figure 3). In these forest plots, abscissa represents SMD and ordinate contains reference of the studies included in the current meta-analyses. The solid square with lines emerging from either end are effect size with confidence intervals (C.I.). The width of the solid square reflects the weight contributed by the respective studies towards the overall effect size.

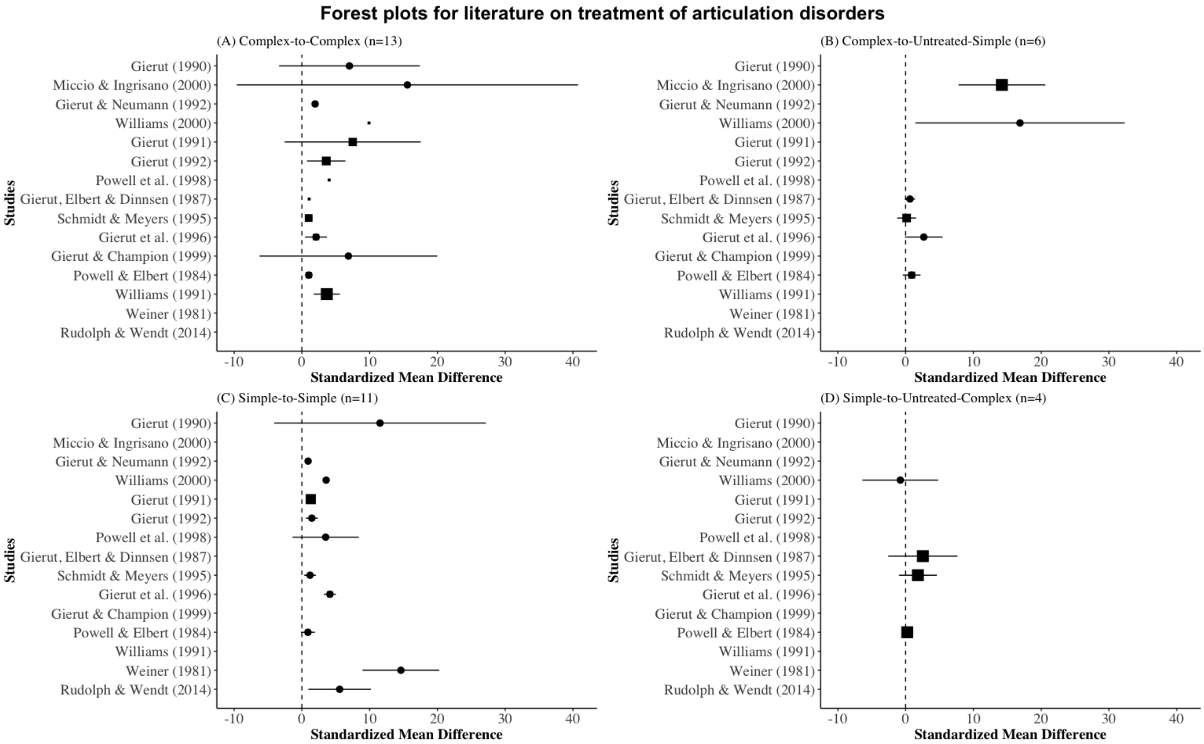

Figure 3. Forest plots depicting the comparison of different therapy approaches for children with articulation disorders. (A): Effect of complexity approach on treated complex sounds; (B) Effect of complexity approach on untreated simple sounds; (C) Effect of simple approach on treated simple sounds; (D) Effect of simple approach on untreated complex sounds

To gain a better appreciation of the comparison of performance of complexity-based approach and traditional-clinical approach, weighted *summary* (overall) effect sizes were plotted separately (Figure 4). The complexity-based approach led to an improvement in complex speech sounds (d = 1.08, n=31, CI = 0.98-1.18) and traditional-clinical approach led to an improvement in simple speech sounds (d = 1.47, n=28, CI = 0.96-1.97). Additionally, the complexity-based approach led to an improvement in the production of simple sounds (d = 2.69, n=10, CI = 1.84-3.54). However, the traditional-clinical approach was unable to promote the production of untreated complex speech sounds (d = 0.24, n=9, CI = 0.15-0.32).

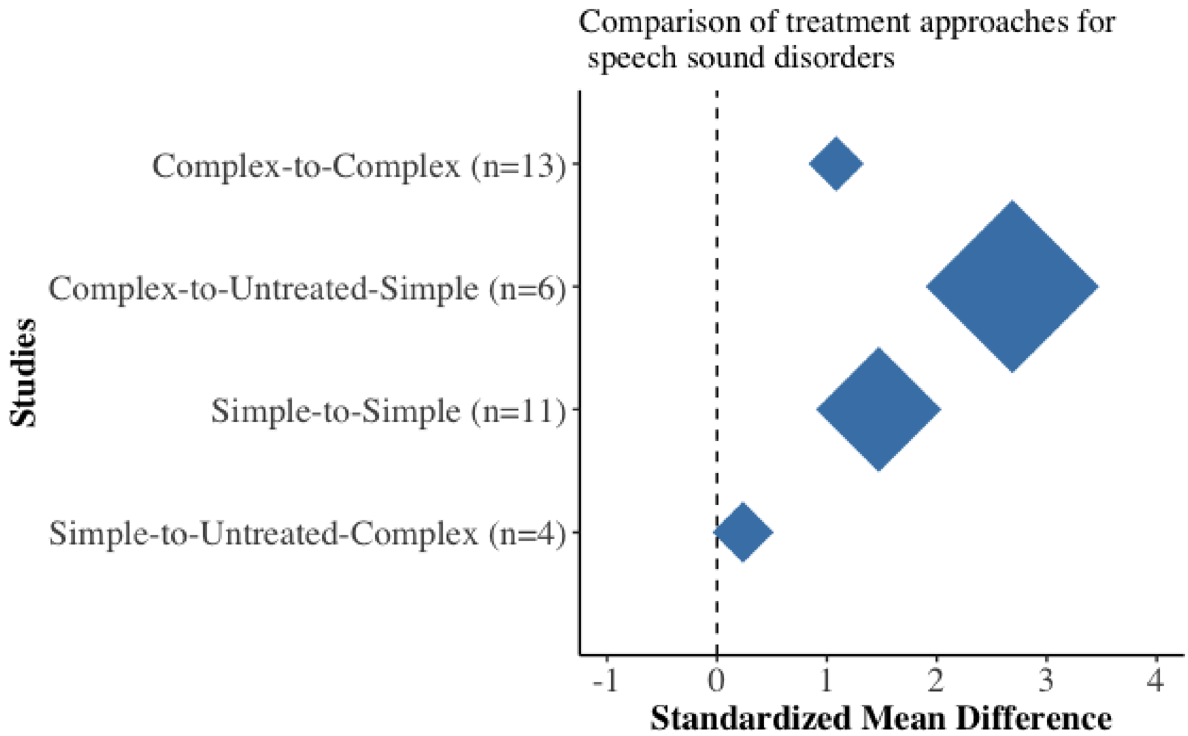

Figure 4. Forest plots (diamonds) depicting a comparison of *summary* (weighted) effect sizes of the treatment procedures.

2.4 Discussion

The current study aimed at contributing to a long-standing debate on whether speech sound acquisition is driven by complex or by simple stimuli. More specifically, we investigated this by reviewing complex and simple therapy approaches of treatment of phonological disorders in a quantitative manner. Based on a meta-analysis review of 15 studies, we found that the complex approach is more successful than the traditional-clinical simple approach in treating children with speech sound disorders. More importantly, the complexity approach led to an improvement in both treated complex speech stimuli and generalized to untreated simple speech stimuli while the simple approach only led to an improvement in treated simple speech stimuli but not complex speech stimuli.

Although the literature related to treatment of speech sound disorders has been reviewed from time to time (Baker & McLeod, 2011; Gierut, 1998; Law et al., 2003, 2004; Nelson et al., 2006), the current systematic review has multiple advantages over the previous review studies. First, the current meta-analysis includes the studies with SCEDs which are the most used designs in phonological treatment studies (Baker & McLeod, 2011) while the previous meta-analyses have included studies only with RCTs (Law et al., 2004; Nelson et al., 2006). Second, the current review focused on a comparison of two major approaches of phonological intervention in children with speech sound disorders while the previous reviews (Baker & McLeod, 2011; Gierut, 1998) have had a broad focus on the effects of intervention. Third, by comparing the complexity and traditional-clinical simple approaches, the current review aimed at answering a more central theoretical question about whether speech acquisition is driven by complexity or by simple input.

The findings of the current meta-analysis revealed that treatment with a complex set of stimuli might prove more beneficial than treatment with simple stimuli. These findings are in agreement with the findings of Gierut and other researchers (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) who suggest the use of a complex set of stimuli for treatment of children with speech sound disorders and are totally consistent with the models of language learning ability as outlined in the context of universal grammar (Wexler, 1982; Wexler & Culicover, 1980). From the current findings, it seems that complex input is more efficacious in triggering and promoting the development of both complex and simple speech sounds in a rule-governed manner. On the other hand, using a less-complex or simple input as stimuli for training may lead to the development of simple speech sounds but does not promote development of difficult or complex sounds. These findings support the poverty of stimulus argument (K. Johnson, 2004; Thomas, 2002) according to which input alone is not sufficient to promote acquisition of language. Rather, there are innate linguistic abilities and when input is mapped, they facilitate the unlocking of simpler structures which furthers the process of acquisition. A plausible explanation for the findings of the current review that supports the notion of innateness could be provided via demotion or differential promotion of OT constraints, resulting from the introduction of complex stimuli. Constraint demotion or differential promotion can only occur when complex stimuli are introduced. For example, in Lleó and Prinz (1996), when a cluster (more marked) was used for training, there was an emergence of correct productions of both clusters and affricates by constraint demotion of markedness constraints of both clusters and affricates. On the contrary, if the affricates (less marked) were used as stimuli, it merely led to the development of affricates by demotion of its markedness constraint beyond the faithfulness constraint. However, it did not promote clusters, mainly because the markedness constraints of clusters still remained higher ranked. In other words, when a complex stimulus is used, it maps on to the complex innate linguistic structures to promote the development of both complex and simpler speech sounds. However, if a simple stimulus is used, it does not lead to the unlocking of other structures.

Along with theoretical implications, the current review also has clinical implications. Phonological disorders, being one of the most prevalent child language disorders, constitute a major portion of caseloads of speech language pathologists (SLPs) dealing with pediatric cases (Baker & McLeod, 2004; Broomfield & Dodd, 2004; Mullen & Schooling, 2010). According to the National Institute on Deafness and Other Communication Disorders (National Institute of Deafness and Other Communication Disorders, 1994), prevalence of phonological disorder ranges from 3 to 13% in the United States. Phonological disorder affects about 10% of the pre-school and school-age children and constitutes about 99% of caseloads of SLPs rendering services at school (NIDCD, 1994). Phonological disorders can be comorbid with primary language impairment and learning disability and these can have a profound impact on a child's academic skills including reading, writing, spelling and mathematics (Bird, Bishop, & Freeman, 1995; Catts, 1993; Catts & Kamhi, 1986; Clarke-Klein & Hodson, 1995; Hoffman, 1990; Hoffman & Norris, 1989; King, Jones, & Lasky, 1982; Lewis & Freebairn, 1992; Shriberg & Kwiatkowski, 1985; Webster & Plante, 1992). Children with phonological disorders usually do not attain similar educational and employment level as their typically developing peers (Dinnsen, 2008; Felsenfeld, Broen, & McGue, 1994). Given the high incidence and lifelong effects of childhood phonological disorders, early identification and intervention, especially for children in their pre- and primary schools, is warranted. A large number of different intervention approaches exist for phonological disorders (Baker & McLeod, 2011; Gierut, 1998). Given the heavy caseload on the practicing pediatric SLPs, they have limited time to review all the relevant evidence for maximizing the effectiveness of the treatment they provide. This meta-analysis can provide them with an empirical basis to employ more efficient, complexity therapy in their clinical practice that may offer greater improvement in a relatively short span of time compared to traditional-clinical simple therapy.

2.4.1 Limitations of the review

There are some limitations to this review mainly because of methodological issues in some of the included studies. First, there was a lack of homogeneity in the study designs of the included studies. Although all the included studies have used SCEDs, 8 of the studies have used multiple baseline AB designs, 1 with a single baseline AB, 1 with a multiple baseline ABA and 5 with a single baseline ABA. As a result, the number of data points available for the calculation of effect sizes varied across studies. Although the weighted average was obtained as a measure of effect size, homogeneity in data can provide us with better statistical power. Second, the studies varied in terms of whether blinding was used or not. Two (13.3%) of the 15 included studies had blinding while others did not. Lack of blinding could lead to Type I error, that is detection of an effect even when there is none (Law et al., 2004). Third, the studies were conducted in different settings ranging from clinical (Gierut, 1990; Gierut & Champion, 1999; Schmidt & Meyers, 1995; Williams, 2000) to home (Gierut, 1991) to school (Miccio & Ingrisano, 2000). Plus, the number of sessions ranged from 7 (Gierut & Champion, 1999) to 20 (Powell et al., 1998). It is not clear how well can findings from one study can be generalized with the findings from another study, given the variability in several realms. Even though we tried to establish optimum inclusion criteria to maintain specificity of the included studies, in an ideal world, one might want to maintain homogeneity in all the above aspects.

2.4.2 Validity of the meta-analysis

There are at least two concerns that can affect the validity of meta-analysis data: (1) Quality of studies: It is possible that meta-analysis results could be affected by the quality of studies included; (2) Selection bias: This could be caused by the inclusion of studies with big effect sizes while selectively ignoring the studies with low or negative effect sizes. This is also known as *bottom drawer* effect (Law et al, 2004). In order to evaluate the likelihood of publication bias (if any), we constructed funnel plots (Figure 5) as a function of standard errors and effect sizes of the studies distributed across the four categories of interest: (A) Complex-to-Complex: Effect of using complex stimuli on treated complex sounds (Figure 5(A)); (B) Complex-to-Simple: Effect of complex stimuli on untreated simple sounds (Figure 5(B)); (C) Simple-to-Simple: Effect of simple stimuli on treated simple sounds (Figure 5(C)); (D) Simple-to-Complex: Effect of simple stimuli on untreated complex sounds (Figure 5(D)). Ideally, if the effect sizes are symmetrically distributed on either side of the average effect size, the meta-analysis is said to be free from publication bias. From the funnel plots of the data extracted in the current review, we found that there were studies on either side (Figure 5) that confirm our study selection was free from publication bias. However, our data do not depict a symmetrical distribution which could be due to main two reasons: (1) *Small sample size and single subject design:* The studies that were included in these analyses had a sample as small as 1 in a single subject design; (2) *Training related improvement:* The current review focused on treatment studies where subjects respond to treatment even though to a minimal degree.

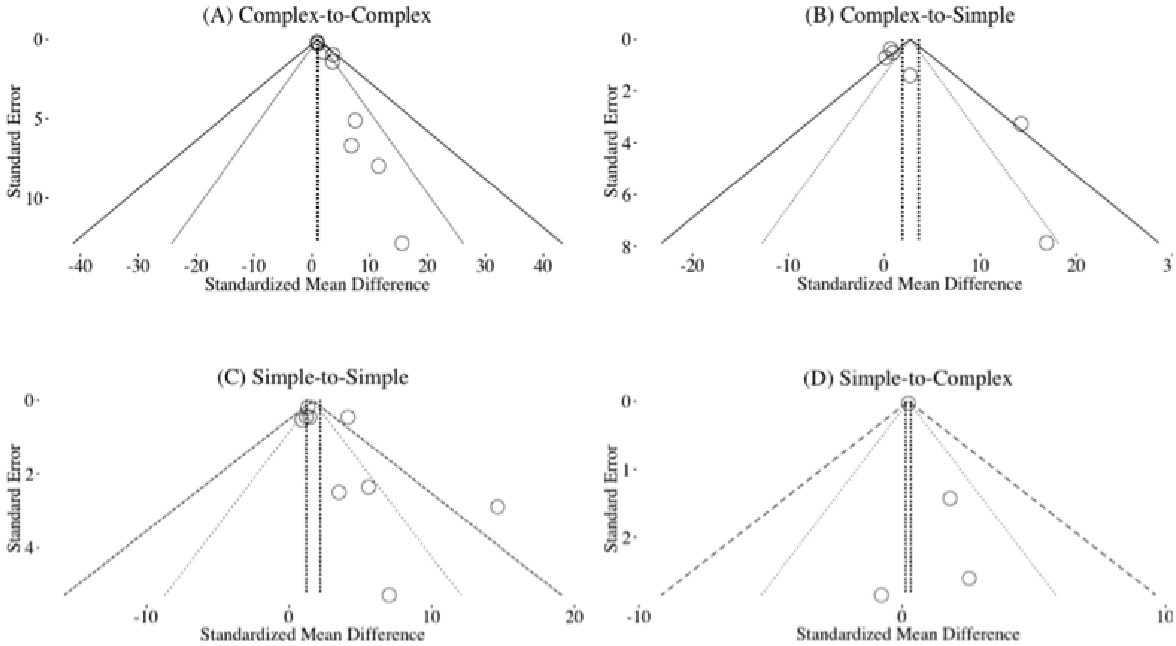

Figure 5. Funnel plots of different conditions. Dotted lines (······) represent 95% CI while striped lines (– –) represent 99% CI. Open circles (o) represent effect sizes plotted against standard error. (A) Complex-to-Complex: Effect of complex stimuli on treated complex speech sounds; (B) Complex-to-Simple: Effect of complex stimuli on untreated simple speech sounds; (C) Simple-to-Simple: Effect of simple stimuli on treated simple speech sounds; (D) Simple-to-Complex: Effect of simple stimuli on untreated complex speech sounds.

2.5 Future directions

Speech language pathology as a profession is relatively young, and it has a shorter research tradition compared to other disciplines such as medicine (Dodd, 2008). Thus, it is unsurprising to find it lacking in the highest level of evidence and accumulation of case studies in the available literature. However, in order to gain more confidence in the treatment-related outcomes, future studies should employ randomized controlled trials that are considered the highest level of evidence by ASHA (Robey, 2004) and the ("Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009)," 2009). In addition, to make more conclusive remarks on the comparison of complex and simple therapy approaches, studies using a variety of speech sounds, different modes of service delivery and subtypes of articulation disorders should be conducted.

Chapter 3

Speech sound disorders - ‘delay’ or ‘deviance’? A Maximum Entropy Grammar modeling approach

3.1 Introduction

Phonological disorders, one of the most prevalent child language disorders (Dinnsen, 2008), are known for their heterogeneity across service delivery settings, populations, and response to different types of treatment (So & Dodd, 1994). Likewise, there is also heterogeneity in the classification of phonological disorders. Several researchers propose that children with phonological disorders are ‘delayed’ (Gierut, 2008; Leonard, 1978) while there are others who suggest that they should be considered ‘deviant’ (Dunn & Davis, 1983; Ingram, 1977; Shriberg, 1982; R. Williams, Packman, Ingham, & Rosenthal, 1980) in their trajectory of speech sound development as compared to typically developing children. Though there have been previous studies (Dodd, 1982, 1993; Dodd, Leahy, & Hambly, 1989; So & Dodd, 1994) that have attempted to further classify the phonological disorder into ‘delayed’ and/or ‘deviant’ subtypes based on clinical descriptive data, the criteria for doing so remains an intriguing question. In the current study, we examined this from a perspective of universal grammar by using Optimality Theory (Prince & Smolensky, 1993) within a Maximum Entropy Grammar (MaxEnt) framework. More specifically, in the current study, we compared the developmental trajectory of weightage of OT constraints of typically developing children and those diagnosed with phonological disorders in order to determine whether children with phonological disorders should be considered ‘delayed’ or ‘deviant’ in their phonological acquisition as compared to typically developing children.

Over the past three decades, a very influential body of literature on learnability by Gierut and coworkers (Elbert, Dinnsen, & Powell, 1984; Gierut, 2001, 2007, 2008; Powell et al., 1991) suggests that children with phonological disorders have an essentially similar patterns of development or developmental implicational hierarchy as children with phonological disorders. The main difference that sets these two groups apart is that children with phonological disorders achieve this constraint hierarchy later than typically developing children, indicating a delay. Gierut and colleagues, on several occasions, using a complexity-based treatment paradigm, have demonstrated that children with phonological disorders could improve in regard to correct production of speech sounds when treated with complex (or more marked) speech stimuli based on the normative implicational hierarchy. For example, if in a child's phonology, both fricatives and stops are affected, then according to Gierut's complexity-based treatment paradigm, the child should be treated with fricatives for them to improve on both fricatives and stops. The basis of this stimulus selection is the implicational hierarchy in typically developing children where fricatives that are more marked imply lesser marked stops (fricatives > stops). On the contrary, if children with phonological disorders do not follow this implicational hierarchy then the generalizability of this treatment approach is questionable. Rvachew and Nowak (2001) believe that though the implicational hierarchy in phonological disorders is uncontroversial, its efficacy in treatment would be assessed on a case-to-case basis.

Although Gierut (2008) suggests that individuals with phonological disorders are more likely to be affected by a delay, there exists individual variability in phonological profiles mainly caused by subjects that do not follow the normative markedness implicational hierarchy (Vihman, Ferguson, & Elbert, 1986; Vihman & Greenlee, 1987). Ingram (1988b, 1988a) believes that it might often be the case that an individual child inventory might go against the predictions of markedness. In other words, there may be children with speech sound disorders that could be considered 'deviant' based on their trajectory of phonological development.

Studies (Bortolini & Leonard, 1991; Dodd, 1982, 1993; Dodd et al., 1989; So & Dodd, 1994; Yavas & Lamprecht, 1988) have been conducted to classify phonological disorders mainly from a clinical developmental perspective. Dodd (1982), from the data of 55 children, found that 56% of the children used normal developmental phonological processes that are commonly used by children of younger ages, and 28% of the children made errors that did not follow phonological processes. Further, Dodd et al. (1989) using a set of experiments focusing on imitation, picture naming and spontaneous speech classified phonological disorders into ‘delayed’, ‘deviant consistent’ and ‘deviant inconsistent’ categories where ‘delayed’ refers to children who use developmental processes inappropriate for their chronological age, ‘deviant consistent’ refers to children using some non-developmental processes and ‘deviant inconsistent’ refers to children making non-rule-governed errors. Yavas and Lamprecht (1988) from articulation data from four Portuguese-speaking children with phonological disorders reported that the children used similar phonological processes (e.g., cluster reduction, final consonant deletion, obstruent devoicing) as used by typically developing children. Bortolini and Leonard (1991) studied four Italian-speaking children (4.9 to 7.1 year olds) with phonological disorders regarding their usage of phonological processes. They found that these children used similar phonological processes as typically developing children (e.g., assimilation, backing and cluster reduction). However, they reported that these children used the processes in a way different from typically developing children. For example, their subjects showed deletion of stops rather than a deletion of sibilants in a cluster.

As we note from the literature, there are considerable studies that have examined the nature of phonological disorders from a clinical and/or developmental perspective. Most of these studies have focused on the individual surface-level errors of articulation to compare them with norms of speech sound acquisition to identify whether the errors constitute a deviance or a delay. Though this approach is clinically relevant, it does not consider the phonological system as a whole. In other words, along with analysis of incorrect productions, correct productions and the phonological environment need to be analyzed to understand the nature of phonological disorder. For example, a child's phonology may consist of sounds that are incorrectly produced for their age in all phonological environments or there might be sounds that the child might produce incorrectly in a specific surrounding vowel context, and then there might be sounds that the child produces correctly in all vowel-contexts. This information is needed as the sounds in the phonological system are linked to one another to bring out phonological patterns. One such phonological pattern is the chain-shift pattern (Morrisette & Gierut, 2008) that usually involves three phonemes (e.g., A, B, C) that are linked to one another by a substitution pattern where sound A is produced as sound B and sound B is produced as sound C, while sound C is produced correctly. These chain-shift patterns are highly prevalent, reported to be occurring in 20% of typically developing children at some point in their phonological development (Dinnsen & Barlow, 1998). In addition, the chain shift patterns have implications towards treatment as the traditional treatment approaches can only lead to limited success in altering the chain shift patterns (Dinnsen & Barlow, 1998; Gierut & Champion, 1999). Besides the chain shift patterns, there are other atypical phonological patterns that cannot be considered as delay in phonological development. For example, consider the error pattern from the phonology of a child from Leonard and Brown (1984). The child's phonology presented with the final consonants replaced by a fricative, insertion of a fricative after word-final vowels and final labial stops preserved. These error patterns depart from the assumptions about acquisition. Knowledge about the complete phonological profile i.e. both correctly and incorrectly produced sounds and their consistency depending on the phonological environment can play a vital role in determining whether a phonological profile is reminiscent of a 'delay' or 'deviance.' In addition, to determine whether abnormal phonological development in children is a result of 'delay' or 'deviance,' it becomes necessary to monitor the trajectory of phonological development across age and compare it to that of typically developing children.

To study the trajectory of phonological development across the age groups, OT provides an excellent tool. OT suggests the role of a set of constraints that are universal in all languages. In OT, the ranking or hierarchy of these constraints governs the surface representation based on a set of underlying representations (i.e., a lexicon). Though the constraints are universal in all languages, it is the difference in the hierarchical arrangement that reveals different outputs across languages. OT postulates the existence of markedness and faithfulness constraints that play key roles in the realization of phonological processes (Prince & Smolensky, 1993). Markedness constraints evaluate output representations only and penalize them for certain configurations. For example, *VOI penalizes voicing. On the other hand, faithfulness constraints consider both input and output ensuring that the output is similar to input with no change. For example, MAX penalizes deletion thus ensuring that the output is the same as the input. It is believed that "if phonology is the computational link between the lexicon and phonetic form, then markedness acts as the advocate of the phonetic interface, faithfulness as the agent of the lexical interface" (Prince & Smolensky, 1993). Based on the demands of these phonetic and lexical modules, the constraints compete against each other to bring out certain rankings. These constraint rankings may also differ within a language at least when typically developing children and those with phonological disorders are compared (Dinnsen, 2008). In typically developing children acquiring language, markedness constraints outrank the faithfulness constraints in the initial state (Smolensky, 1996). With acquisition taking place, markedness constraints fall lower in the hierarchy while faithfulness constraints rise up the hierarchy. In order to understand and gauge the phonological development in children, hierarchical arrangement of OT could provide a suitable framework (Dinnsen, 2008).

Though traditional OT has been one of the dominant theories to account for phonological acquisition and development, there are certain caveats to its use, particularly with phonological disorders. First, in traditional OT, we can only obtain a single OT constraint ranking from the data. Thus, traditional OT cannot model grammars containing free variation, where a single input form has more than one grammatical output form. Second, traditional OT cannot learn from noisy training data. Third, traditional OT cannot account for *cumulativity* effects where a few lower-ranked constraints can combine to militate against a stronger constraint. Fourth, traditional OT offers a categorical view of constraint rankings. Data from children with phonological disorders often contain free-variations and are generally noisy. These problems of traditional OT can be overcome by using a Maximum Entropy Grammar (MaxEnt) approach. MaxEnt modelling is based on general statistical maximum entropy models that are widely used in other domains with their well-known mathematical properties. MaxEnt has been used vis-à-vis OT (Eisner, 2000; M. Johnson, 2002) to efficiently deal with free variations and noisiness in the data (Goldwater & Johnson, 2003). In addition, the MaxEnt approach can account for cumulativity effects and provide a quantitative view (in terms of weightages) of constraints in action.

Given there is little consensus on the classification of phonological disorders and shortcomings of the previous methods of examining the data, in the current study, we investigated this question by comparing the trajectory of speech sound development of 3-6-year-old typically developing children with those diagnosed with phonological disorders. Specifically, we examined this question from a universal grammar perspective by employing

OT constraints in a MaxEnt framework. We hypothesized that phonological disorder can range from 'deviance' to 'delay' depending on the trajectory of development of constraint weightages across the groups of 3-6-year-old children. We predicted that for the 'delay' subtype, the trajectory of development of constraint weightages would be similar to that of typically developing children while for the 'deviance' subtype, a different trajectory of development of constraint weightages across the age groups would emerge.

3.2 Method

3.2.1 Participants

All participants (N = 61) were children in the age range of 3-6 years from Cantonese-speaking homes in Hong Kong. Participants who were beyond 1.5 SD on the normative scores of the Hong Kong Cantonese Articulation Test (HKCAT) constituted the phonological disorder group (n = 31) while those who were within 1.5 SD of the HKCAT normative scores constituted the group of typically developing (TD) children (n = 30). Table 5 describes the distribution of subjects across the age groups and disorder-status. They had peripheral hearing sensitivity within 25 dB HL at 0.5 to 4 kHz, no history of middle ear pathology, and no obvious anatomical/neurological defects.

Table 5. Distribution of subjects across age range and diagnosis

Age range (year; months)	**Speech Sound Disorder (SSD)**	**Typically Developing (TD)**
3 – 3;11	12 (40 ± 3.5 m; 4 F)	9 (41 ± 3.35 m; 4 F)
4 – 4;11	9 (54.33 ± 2.06 m; 5 F)	10 (50.55 ± 2.5 m; 7 F)
5 – 5;11	10 (66.4 ± 3.78 m; 9 F)	11 (65.5 ± 2.74 m; 4 F)

3.2.2 Material

All the participants were administered with HKCAT (Cheung, Ng & To, 2006) which contains 42 color photographs to elicit 51 familiar words containing all the consonants, vowels, diphthongs and tones that occur in Cantonese.

3.2.3 Procedure

All the participants were tested individually in a quiet room in their nursery schools or kindergartens. After establishing rapport, the stimulus book of HKCAT was administered. To elicit a response from the participants, a standard carrier question was asked by the tester showing the picture stimulus. The participants were expected to produce a response spontaneously but if they found it difficult to produce a response spontaneously (especially very young children), they were given the word by the testers for imitation. An imitated response was treated the same way as a spontaneously produced response. Speech samples were recorded using a lapel microphone attached to the children's clothing and stored in minidisc recorders (Sony Mz-B100 or Sharp MD-MT290H(S)). After collecting the speech samples, two experienced listeners of speech recordings transcribed and scored the samples.

3.2.4 Analysis

Based on the transcribed data from these 61 3-6-year olds, we looked for phonological patterns. We found four major patterns in their speech samples, namely manner change (stopping, frication and affrication), place change (fronting and backing), aspiration change (de-aspiration) and consonant deletion (cluster reduction) (Table 6).

Table 6. Four major patterns of errors

Type of change		Definition	Example
Manner	Stopping	A fricative or affricate is substituted with a plosive.	/ts/→[t]
	Frication	A plosive or affricate is substituted with a fricative.	/ts^h/→[θ, s]
	Affrication	A plosive or fricative is substituted with an affricate.	/s/→[ts]
Place	Fronting	A back consonant is substituted with a front one.	/k/→[t]
	Backing	A front consonant is substituted with a back one.	/p^h/→[t^h]
Aspiration	De-aspiration	An aspirated plosive is substituted with its unaspirated counterpart.	/p^h t^h k^h /→[p t k]
Deletion	Cluster reduction	The consonant cluster /k(h)w/ is reduced to the velar plosive or the labial-velar glide.	/kw/→[k]; /kw/→[w]

Based on these patterns we selected the OT markedness and faithfulness constraints from the literature (De Lacy, 2006; Kager, 1999; Ringen & Heinämäki, 1999). Table 7 provides a description of all the selected constraints with their functions. Constraints (a)-(g) were selected to capture the manner change. Constraints (a)-(c) imply the markedness of stops in different places of articulation. That is, a [+dorsal] stop is more marked than a [+labial] stop, and they are both more marked than a [+coronal] stop. Constraints (d) and (e) imply that a [+coronal] fricative is less marked than a [+dorsal or [+labial] stop. Constraint (f) is a markedness constraint that prevents affricates (De Lacy, 2006). Constraint (g) is a faithfulness constraint that prevents any manner change from the input to the output. Constraints (h)-(k) capture the place change. Constraints (h), (i) and (j) are markedness constraints, and they ban consonants that are [+dorsal], [+labial] and [+coronal], respectively. The constraint hierarchy *{dors} >> *{lab} >> *{cor} indicates that the [+coronal] sounds are less marked than [+dorsal] or [+labial] sounds (De Lacy, 2006). Constraint (k) is a faithfulness constraint, and it requires the place feature of the consonant to be maintained in the output. Constraints (l) and (m) capture de-aspiration, and they are markedness and faithfulness constraints, respectively. The former bans aspirated obstruents, while the latter preserves the specification for [spread glottis]. The constraints (n)-(p) capture cluster reduction. Specifically, constraint (n) prevents consonant clusters in the output, constraint (o) requires at least one consonant to occupy the onset in the output, and the faithfulness constraint (p) prevents consonant deletion from the input to the output.

Table 7. Description of OT constraints employed to account for the pattern of errors.

OT Constraints	Constraint Index	Description	Type	Function
a. *{dors}	C1	Assign a violation for each [dorsal] feature.	Markedness	Ban [k, k^h, kw, k^hw, j, w].
b. *{lab}	C2	Assign a violation for each [labial] feature.	Markedness	Ban [p, p^h, f, m]
c. *{cor}	C3	Assign a violation for each [coronal] feature.	Markedness	Ban alveolar consonants in the output.
d. Onset	C4	Each syllable must have an onset.	Markedness	Prevent syllables without onset in the output.
e. ident {place}	C5	The specification for place of articulation of an input segment must be preserved in its output correspondent.	Faithfulness	Prevent place change in the output.
f. *{dors}/stop	C6	Assign a violation for each stop with a [dorsal] feature.	Markedness	Ban [k, k^h, kw, k^hw, ŋ]
g. *{dors,lab}/stop	C7	Assign a violation for each stop with a [dorsal] or [labial] feature.	Markedness	Ban [k, k^h, kw, k^hw, ŋ] and [p, p^h, m]
h. *{dors,lab,cor} /stop	C8	Assign a violation for each stop with a [dorsal], [labial] or [coronal] feature.	Markedness	Ban [k, k^h, kw, k^hw, ŋ], [p, p^h, m] and [t, t^h,n]
i. *{dors,lab}/fricative	C9	Assign a violation for each fricative with a [dorsal] or [labial] feature.	Markedness	Ban [f, θ]
j. *{dors,lab,cor} /fricative	C10	Assign a violation for each fricative with a [dorsal], [labial] or [coronal] feature.	Markedness	Ban [f, θ] and [s, ʃ]
k. *AFFR	C11	Affricates are banned.	Markedness	Ban [ts, ts^h]
l. ident {manner}	C12	The specification for the manner of articulation of an input	Faithfulness	Prevent manner

		segment must be preserved in its output correspondent.		change in the output.
m. *AspObs	C13	Aspirated obstruents are banned.	Markedness	Ban [pʰ, tʰ, kʰ, kʰw, tsʰ, h]
n. ident {[sg]}	C14	The specification for the feature [spread glottis] of an input segment must be preserved in its output correspondent.	Faithfulness	Prevent de-aspiration in the output.
o. *Complex(Onset)	C15	No clusters are produced in the onset position.	Markedness	Ban [kw, kʰw]
p. Max	C16	Each input must have a correspondent in the output.	Faithfulness	Prevent deletion in the output.

3.2.4.1 How the MaxEnt tool works

In the current study, we used these constraints in Table 7 for analysis using the MaxEnt grammar tool (Hayes, Wilson, & George, 2009). The MaxEnt grammar tool provides us an objective way of determining the constraint weightages. The overall goal of MaxEnt is to maximize the probability of the observed forms which is possible only by minimizing the probability of the unobserved forms that differ from the observed forms in a principled manner as guided by the set of constraints. Initially, all the constraints are given the maximum weight, which is "1". As we run the analysis with the goal of maximizing the probability of occurrence of the observed forms, we find the constraints to be affecting the observed form to different degrees. The occurrence of an observed form *x* can be calculated by the following equation

$$h(x) = \sum_{i=1}^{n} w_i C_i(x) \qquad (3)$$

where

w_i is the weight of the i^{th} constraint

$C_i(x)$ is the number of times x violates the i^{th} constraint

$\sum_{i=1}^{N}$ denotes summation over all the constraints ($C_1, C_2, \ldots\ldots, C_N$)[2]

This equation explains that in order to get an observable form in the output, the constraints need to co-ordinate with each other to different degrees leading to different weightings in the MaxEnt output.

Table 8. Example input table for the MaxEnt Grammar Tool

			*AFFR	ident {manner}
Input	Candidates	Frequency	C1	C2
ts	t	5		1
	s	0		1
	ts	1	1	

Here is an example of an input table for MaxEnt (Table 8). The first column gives the input, namely, the citation form of the consonant. The second column lists the output candidates, i.e. the possible productions. The third column shows the frequency of the candidates. Specifically, "5" indicates that the candidate [t] occurred five times in the children's production, "0" indicates that the candidate [s] did not occur, and "1" indicates that the candidate [ts] occurred once. The fourth and fifth columns give the full names of the constraints and their abbreviations, respectively. The numbers below the constraint names indicate the number of times a candidate violates the constraints, and a blank cell means that the candidate does not violate the constraint. For example, the input in the table is the affricate /ts/, and the output candidates are the stop [t], the fricative [s] and the affricate [ts]. [t] and [s] do not violate *AFFR, while each of them violates ident{manner} once. On the other hand, [ts] violates *AFFR once.

Based on the input, possible productions, constraints, candidate frequency and violation count (see Appendix-B for an example of input table for the current data), MaxEnt tool brings out constraint weightings. Based on the availability of the current data, we selected four pairs of markedness and faithfulness constraints for the major patterns of consonant change. First, we compared the faithfulness constraint that bans manner change (ident{manner}) with the markedness constraint that bans affricates (*AFFR), as de-affrication (stopping, frication) is more common than affrication. Second, we compared the faithfulness constraint that preserves the place feature (ident {place}) with the markedness constraint that bans [+labial] or [+dorsal] feature specification (*dor/*lab), as [+labial] and [+dorsal] sounds are more marked than [+coronal] sounds. Third, the faithfulness constraint (ident {[sg]}) and the markedness constraint (*AspObs) were compared: the former requires maintaining the aspiration feature of the obstruent, while the latter prevents aspiration obstruents in the output. Fourth, consonant cluster reduction reflects the conflict between MAX and *Complex(Onset): MAX is a faithfulness constraint that prevents consonant deletion, while *Complex(Onset) is a markedness constraint that disallows consonant clusters to occupy syllable onset.

3.3 Results

3.3.1 MaxEnt analyses

In order to determine and compare the trajectory of change (with age) of constraint-weightings for the TD children and those with SSD, we treated the data within each subgroup (see Table 5 for information on subgroups) as a corpus for the MaxEnt to train on with the selected constraints. For example, data from all 12 SSD subjects from 3-3;11 years were pooled together so that MaxEnt works on it to bring out weightings for the set of constraints. As a result, for each subgroup, we obtained the weightings of each constraint. As markedness and faithfulness constraints complement each other and change differentially across the course of development, and as MaxEnt allows additivity of constraint weightages, we subtracted weightings of markedness constraints from the weightings of their corresponding faithfulness constraints in each subgroup to calculate the *correct production (CP)* index. For example, for the markedness constraint *AFFR, the corresponding faithfulness constraint is ident {manner}. So, the CP index for this set of constraints would be ident {manner} minus *AFFR. Higher CP Index indicates more adult-like productions of speech sounds. We compared the trajectory of CP indices across age (3-6 years) and subgroups (TD, SSD) (Figure 5). For all sets of markedness and faithfulness constraints, we could observe that there was an increase in the magnitude of the CP index for TD children across age while for children with SSD, there was no increase (or even a slight decrease) in the CP index across age. In other words, the slope or trajectory of development for TD children and those with SSD is not similar. These data revealed that the subjects with SSD depict a deviant rather than a delayed trajectory of development of constraint weightings.

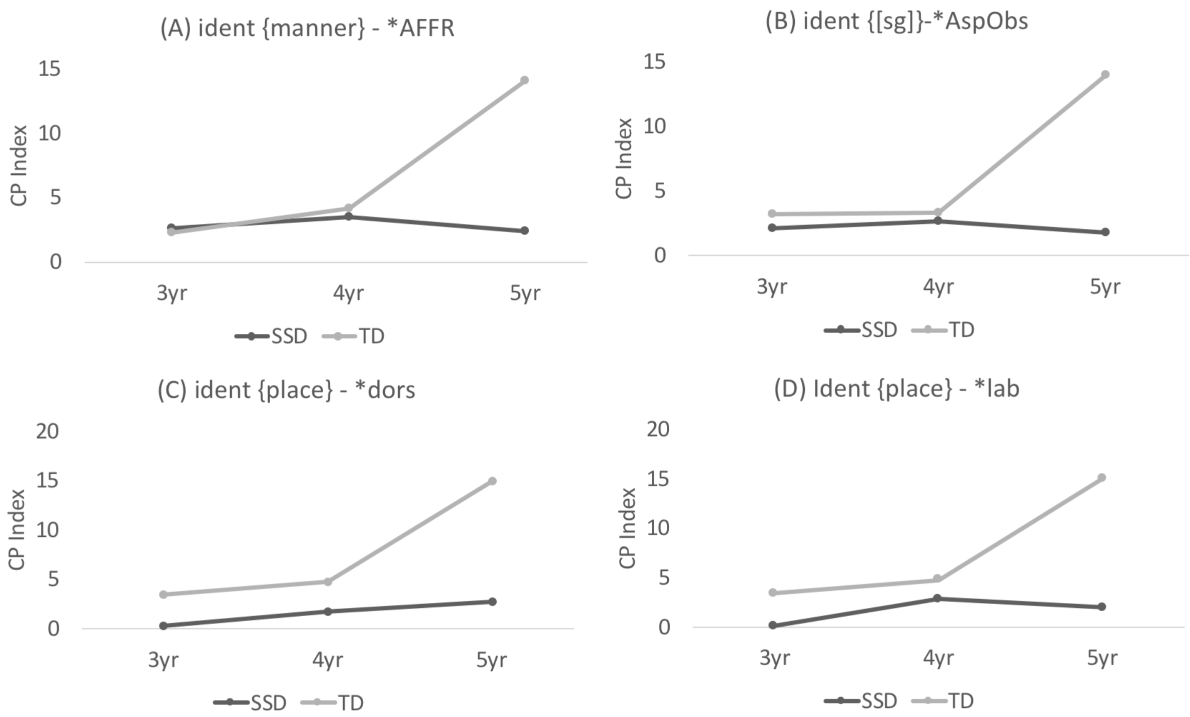

Figure 6. CP index for TD and SSD groups plotted across age (3-5 years). Panels A-D: Different trajectory of constraint development for the TD and SSD groups.

Along with using all the data as a corpus, we also conducted an in-depth case-by-case inspection of the data. For this, we constructed confusion matrices for input and output speech sounds for subjects in each subgroup. Based on the productions, we found that children in the TD group followed the normative developmental markedness hierarchy that is needed to promote the acquisition of speech sounds. For example, a child may produce a lesser marked stop for a more marked fricative. In the SSD group, on the other hand, we found that a few children depicted the phonological patterns against the normative developmental markedness hierarchy. For example, with a stop as an input, a child may produce a fricative in the output. This clearly violates the developmental markedness hierarchy. Overall, we found that seven children (4 in the 3-3;11 year; 2 in the 4-4;11 year and; 1 in the 5-5;11-year-old subgroup) in the SSD group had speech productions that violated the developmental markedness hierarchy while the other 24 had speech productions that followed the markedness hierarchy (see Appendix-A for confusion matrices of SSD children). Thus, we further segregated the SSD data into those who followed the markedness hierarchy (SSD-1) and those who did not follow the developmental markedness hierarchy (SSD-2) (Table 9).

Table 9. Distribution of subjects across typically developing children, newly-formed SSD-delayed and SSD-deviant subgroups and age

Age	**SSD-1**	**SSD-2**	**TD**
3 – 3;11	8	4	9
4 – 4;11	7	2	10
5 – 5;11	9	1	11

We ran separate MaxEnt analyses for all the subgroups (SSD-1, SSD-2 and TD) to understand their trajectory of change across age. We found that the TD and SSD-1 groups showed similar patterns of trajectories of development with the difference being that the SSD-1 subgroup demonstrated reduced CP weightings as compared to the TD subgroup. In contrast, the trajectory of development of SSD-2 subgroup exhibited a totally different pattern in comparison to both TD and SSD-1 subgroups (Figure 7).

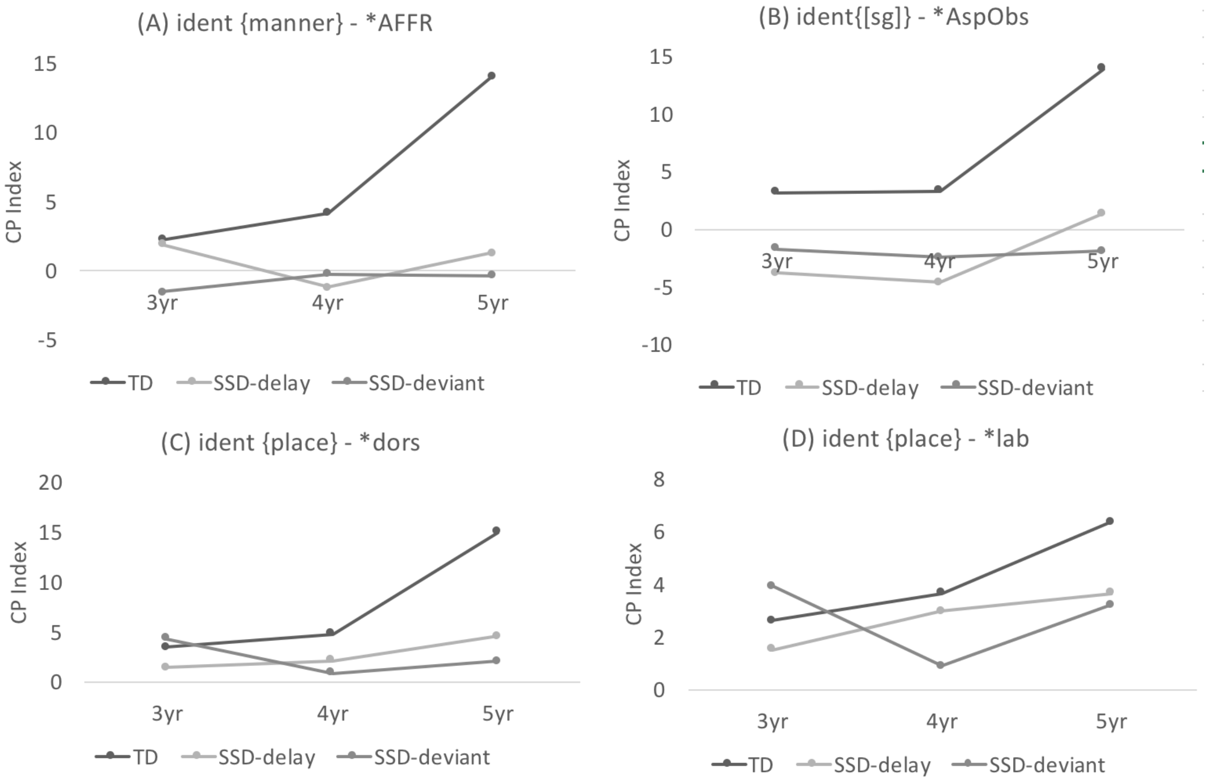

Figure 7. CP index for TD, SSD-delay, SSD-deviant subgroups plotted across age (3-5 years). Panels A-D: Similar trajectory of constraint development of the TD and SSD-delay subgroups with a different trajectory of constraint development for the SSD-deviant subgroup.

3.3.2 Quantitative comparison

Further, in order to quantitatively compare the three subgroups, we analyzed the trajectory of development of production accuracy for place, manner and affricate production. We found similar results as in section 3.1, i.e. the TD and SSD-delay subgroups demonstrated a similar trajectory of development while children with SSD-deviant subtype had a deviant trajectory as compared to the other two subgroups (Figure 8).

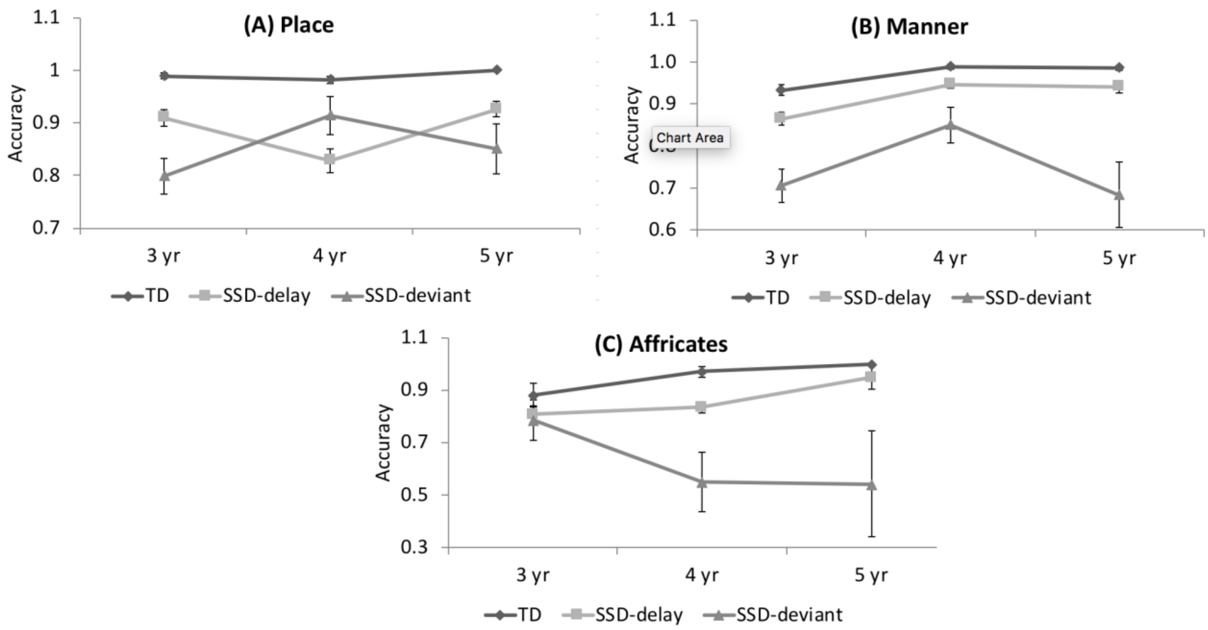

Figure 8. Quantitative comparison of accurate production of (A) Place of articulation; (B) Manner of articulation; and (C) Affricate production. Panels A-C: Similar trajectory of development of production for the TD and SSD-delay subgroups with a different trajectory of development of production for the SSD-deviant subgroup.

3.4 Discussion

In the current study, we investigated whether children with phonological disorders depict ‘delay’ or ‘deviant’ profiles. We examined this by comparing the speech sound production profiles of 3-6-year-old typically developing children with those with phonological disorders. Instead of simply comparing the acquisition of each sound in isolation, we considered the whole phonological system by comparing the trajectory of development of OT constraints. Based on the data, we selected markedness and faithfulness OT constraints for place, manner, aspiration and cluster reduction that were further used in the MaxEnt approach to derive their weightings on the data. By conducting an in-depth linguistic analysis, we found that children with SSD could have a ‘delay’ or a ‘deviant’ subtype. The main difference between the ‘delay’ and ‘deviant’ subtypes was that SSD children with ‘delay’ exhibited a similar trajectory of development of constraint weighting as TD children while children with ‘deviant’ profiles depicted a totally different developmental trajectory as compared to typically developing children.

The current study is one of the first attempts at the classification of phonological disorders based on analysis of the phonological system as a whole. Though the previous studies (Dodd, 1982, 1993; Dodd et al., 1989; So & Dodd, 1994) have classified phonological disorders based on the presence of phonological processes and normative data, there have been no studies that have captured the phonological system as a whole. In this study, we found that the children affected with the ‘delay’ subtype of phonological disorder have a similar trajectory with a reduced magnitude of CP index (faithfulness minus markedness weighting). This is mainly because these children produce many sounds incorrectly as compared to TD children, but the pattern of sound change is similar to that of TD children. For example, for a fricative sound /s/ for which a TD child produces [s] 90% of the time and [t] for the remaining 10% of the time, a child with ‘delay’ might produce [s] 30% of the time with the production of [t] 70% of the time. On the contrary, a child with ‘deviance’ might produce [ts] for the input /s/ for 100% of the time, which is against the normative pattern of change. By just comparing with the normative scores of the individual sounds produced in isolation to diagnose phonological disorders in children, one can easily miss the nature of the phonological disorder. Thus, the findings from the current study stress the need to consider the overall phonology of children to identify the aspects that are impaired and those that are intact.

Based on the current findings on the classification of speech sound disorders as ‘delay’ vs ‘deviant,’ there are clinical implications towards diagnosis and choice of therapy technique. Especially, the type of therapy to be used with children affected by a ‘delay’ vs. those who are affected by ‘deviance’ might differ. Over the past three decades, a very influential body of research on learnability from Gierut and coworkers (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) suggests that treatment plans should be based on the markedness hierarchy seen in typically developing children. The premise behind this approach is that children with speech sound disorder have a similar but delayed course of development. As a result, using speech stimuli that are more marked or complex on the normative markedness hierarchy can bring these children "back on track." While this approach seems appropriate for children with 'delay,' this approach might not work for those affected with 'deviance.' For example, consider a child with 'delay' that produces [t] for /s/ and /ts/. Now as we know that on the markedness hierarchy, affricates > fricatives > stops, treating with a sound /ts/ that ranks higher in the markedness hierarchy might promote generalization of the lesser marked fricatives and stops. As a result, there might be an improvement in both /ts/ and /s/. However, for a child that produces [ts] for /t/ and /s/, the use of complex stimuli in therapy might not work successfully, mainly because the child is able to produce the more marked or more complex [ts] sound correctly but not the simple or lesser marked sound (/t/). So, in order to treat these children, one can consider using traditional clinical approaches (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973; Hodson, 2006; Hodson & Paden, 1991; Mota et al., 2007; Pascoe et al., 2005) where children with speech sound disorders are treated with simple sounds first using sound perception and production drills. So, in this case, the child's treatment should begin with /t/ sound as the input. Recently, Rvachew and colleagues (Rvachew, 1994; Rvachew et al., 2004, 1999) have shown that children who are treated with simple or stimulable sounds first remain more motivated to attend therapy sessions and show more overall improvement. As a result, there is more scope for improvement in 'deviant' children using simple speech sounds first as compared to complex speech sounds. However, after exposing these children to simple input to increase their stimulability, they can be later exposed to complex input.

Besides the benefits to the patients, determining the subtype of speech sound disorder could prove advantageous to service providers. Speech sound disorders constitute a huge portion of caseloads for speech language pathologists (SLPs) dealing with pediatric cases (Baker & McLeod, 2004; Broomfield & Dodd, 2004; Mullen & Schooling, 2010). According to the National Institute on Deafness and Other Communication Disorders (National Institute of Deafness and Other Communication Disorders, 1994), the prevalence of speech sound disorder ranges from 3-13% in the United States affecting around 10% of pre-school and school-age children, and constituting about 99% of caseloads of SLPs rendering services at schools. Given the heavy caseload and busy clinical routines, it will be beneficial for school SLPs to optimize treatment to match the needs of the children (based on their subtype) to maximize the benefits in a shorter time.

3.5 Future Directions

The current findings, based on the linguistic analyses of the phonological data of typically developing children and those with speech sound disorders reveal that there might be subtypes of speech sound disorder. The current findings were based on data from the production of the initial consonants, and selected markedness and faithfulness constraints. Future studies could be conducted with other languages with richer phonological inventories to understand whether or not the constraint weightings and patterns are similar to the current study. In addition, the current findings were from data obtained from 3-6 year old children. Future studies could consider obtaining data from more age groups cross-sectionally. Even better would be to conduct a longitudinal investigation that could account for individual differences. Further, based on the subtypes, we speculate that the effectiveness of treatment approaches might differ. Future studies could further investigate this by comparing the effects of different types of treatment techniques on children with different subtypes of speech sound disorder.

Chapter 4

Complexity drives speech sound development: Evidence from artificial language training

4.1 Introduction

Learning is heavily shaped by experience and its effects are fairly permanent. An ongoing debate in the field of learning is whether experience with hard/less frequent/marked/atypical stimuli (hereafter, complex stimuli) at the beginning maximizes the benefits or learning with easy/more frequent/unmarked/typical stimuli (hereafter, simple stimuli) first is the most beneficial. Traditionally, learning proposedly occurs by slow and steady building of concepts starting from the simplest and then progressing to more difficult ones, hereafter *simple-learning theory*. Quite recently, studies from different domains (Eckman et al., 1988; Gierut, 2007; Kuhn, 1972; Özgün & Barlas, 2013; Plaut, 1996; Yao, 1989) have stressed the importance of using complex stimuli first to induce far-reaching effects, hereafter *complex-learning theory*. In order to contribute towards understanding whether learning with complex or learning with simple input is more efficient, in the current paper, using behavioral and electrophysiological measures, we compared the performance of subjects who learned complex speech stimuli vs those who learned simple speech stimuli in a 5-session artificial pseudo word-picture association paradigm.

Research on learning by complex and by simple input is well documented in literature of several scientific fields including cognitive development (Kuhn, 1972; Piaget, 1962), motor skill acquisition (R. A. Schmidt & Lee, 2005; Wulf & Shea, 2002), computational modelling (Elman, 1993, 1998; Plaut, 1996; Rohde & Plaut, 1999), second language learning (Eckman et al., 1988), phonological disorders (Gierut, 2007; Rvachew, 2005), language disorders

(Kiran, 2007; Kiran & Thompson, 2003; Thompson & Shapiro, 2007), gaming (de Jong et al., 1999; James & Stephen, 1994; Özgün & Barlas, 2013; Yasarcan, 2010), and math learning (Yao, 1989). Using computational modelling, Elman (1993) found that “starting small” or starting with simpler elements leads to enhanced learning while Rohde and Plaut (1999), using a pseudogrammar computational framework, revealed that exposing the system to full grammar all at once led to more effective learning. Further, Plaut (1996) using a computer-simulated lexical-semantic network found that when the system was impaired, more benefits would take place when it was trained with complex stimuli rather than simple stimuli. In the field of education, traditionally it is believed that the students should be taught new concepts in a scaffolding manner with an increasing gradation of difficulty (Vygotsky, 1962). On the other hand, Eckman et al. (1988) found that in teaching English to non-native speakers, use of complex relative clauses led to greater generalization to untrained simple sentences as compared to teaching simple relative clauses. In the gaming literature, Yasacran (2010) revealed that starting to play simpler versions of a game before going to more complex levels were the key to greater gaming performance. On the other hand, de Jong et al. (1999) reported that they found no difference in performance of the group of subjects who trained on all five levels of a game in an increasing complexity as compared to the subjects trained on just last three levels of the game. Further, James and Stephen (1994) found that the strategy of breaking the game into sections of increasing complexity was less efficient than presenting the subjects with the whole task at once. In the field of cognitive science, according to Piagetian theory (Piaget, 1962), development of cognition in individuals takes place in a step-by-step manner with increasing complexity at each step. On the other hand, Kuhn (1972) taught children with stimuli from later Piagetian stages and found that these stimuli induced greater generalization than the stimuli from the earlier stages. So, based on the above findings from computational modelling, gaming, cognitive science and second language learning, we infer that there is no clear consensus on whether it is complex input or simple input that maximizes learning.

In the domain of language, in order to understand whether it is learning via complex input or learning via simple input needed to promote more development, treatment-based studies have been conducted in the area of phonology (for e.g., Gierut, 2007), lexical-semantics (for e.g., Kiran, 2007), and syntax (for e.g., Thompson & Shapiro, 2007). In order to test the applicability of the competing theories on the importance of training with complex vs simple stimuli, treatment- or training-based studies play an important role as they allow selective manipulation of variables to observe effects in the populations with disorders (Gierut, 2008). For evaluating the efficacy of treatment- or training-based studies, generalization has been considered as a gold standard, without which the benefits of any treatment or training paradigm remain questionable (Thompson, 2007). Generalization, in its most limited sense, can be defined as the extension or transfer of learning from trained to untrained stimuli (Gierut, 2001). Generalization is a measure of applicability of treatment in the real world, and success of a treatment is directly proportional to the quantum of the induced generalization as a result of treatment.

In syntax, most of the treatment studies, using complex or simple input, have been conducted on patients with aphasia. Complexity in syntax studies can be manipulated based on the type of sentence forms. For example, sentences with *why*-movement, such as object relative structures (e.g., "The man saw the cat who the dog chased") are considered complex as compared to simple active sentences (e.g. "The dog chased the cat"). The two widely used aphasia treatment techniques are *mapping therapy* (Byng, 1988; Jones, 1986; Schwartz, Saffran, Fink, Myers, & Martin, 1994) and *"treatment of underlying forms"* (TUF;

Thompson & Shapiro, 2007). Mapping therapy targets the sentence production deficits, most commonly seen in patients with aromatic Boca's aphasia (Schwartz et al., 1994), and basically aims at treatment of subjects by helping them map the underlying "meaning relations" within sentences. Another approach, TUF, exposes the patients treated with complex sentence forms as opposite to simple sentences (active sentences). While both mapping therapy and TUF contains steps for training thematic roles, TUF seems to be a more comprehensive technique than mapping therapy because TUF focusses on both comprehension and production while the mapping therapy focuses only on comprehension. Additionally, mapping therapy begins with training syntactically simple sentences first while TUF uses complex sentences as a starting point (Thompson & Shapiro, 2007). Schwartz and colleagues' mapping therapy technique consists of a patient learning by query in a step-by-step manner (Dorze, Jacob, & Coderre, 1991; Fink, Schwartz, & Myers, 1998; Jones, 1986; Marshall, Pring, & Chiat, 1993; Schwartz et al., 1994). Schwartz (1994) taught the patients to identify verbs and lexical items by a series of queries. Since then, there have been many variants (Berndt & Mitchum, 1997; Haendiges, Berndt, & Mitchum, 1996; Mitchum, Haendiges, & Berndt, 1995; Rochon, Waters, & Caplan, 1994) of this approach focusing on different aspects. On the other hand, Thompson and colleagues from their series of studies (Ballard & Thompson, 1999; Thompson, Shapiro, Kiran, & Sobecks, 2003; Thompson, Shapiro, & Roberts, 1993; Thompson, Ballard, & Shapiro, 1998) report that treating patients with complex sentential structure is more efficacious as compared to teaching with simple sentences.

In lexical-semantics, studies have been conducted on patients with aphasia that depict some form of naming deficits. Depending on the type of aphasia, naming deficits may vary from neologisms in Wernicke's aphasia to problems in word retrieval due to defective semantic system in Boca's aphasia. In fluent aphasia, the naming deficits are believed to arise from incorrect activation of semantic nodes. To treat naming deficits, both traditional-clinical (i.e., using simple stimuli) and complex-stimuli techniques have been proposed. In the traditional-clinical method, the patients are given typical exemplars as tokens for the naming therapy while in the complexity-driven therapy patients are provided with atypical exemplars. Typical exemplars possess more prototypical features and less distinctive features while the atypical exemplars possess more distinctive features. For example, *sparrow* and *pigeon* are typical exemplars of birds as they possess more prototypical features (e.g., *has wings, can fly*) and less distinctive features *(e.g., long neck, big beak)* while *ostrich* and *penguin* are atypical exemplars of birds as they possess more distinctive features *(e.g., long neck, runs, long legs)* and also has core features of birds *(e.g., lays eggs, has beak)*. Traditional-clinical method is to teach the patients with naming of birds with basic features first (typical exemplars) and then go to complicated concepts (atypical ones). On the other hand, Kiran and Thompson (2003) reveal that treatment with atypical exemplars directly leads to more generalization towards both atypical and typical exemplars while treatment with typical exemplars could not generalize to atypical ones.

In the domain of speech learning, several behavioral studies have been conducted that show learning of novel speech sounds using different techniques of training (Bradlow, Akahane-Yamada, Pisoni, & Tohkura, 1999; Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Perrachione, Lee, Ha, & Wong, 2011; Wong & Perrachione, 2007). However, these studies do not compare the effects of learning via complex vs simple speech sounds. In the field of phonology, there are a few learning studies that have compared the effects of using conducted using complex and/or simple input. Learning with complex input is supported by linguistic theories compatible with the principles of universal grammar, including generative grammar

(Chomsky & Halle, 1968), natural phonology (Stampe, 1979), and optimality theory (Jakobson, 1968; Prince & Smolensky, 1993b; Trubetzkoy, 1969). On the other hand, learning with simple input is supported by the traditional theories compatible with the "simple first" principle, including behaviorist theories (Skinner, 1957), scaffolding theories (Piaget, 1962; Vygotsky, 1962), connectionist view (Elman, 1993), and dynamic systems theories (De Bot et al., 2007; Rvachew & Bernhardt, 2010). Gierut and coworkers (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) have used markedness hierarchy as a means to define phonological complexity. Markedness hierarchy describes implicational relationships between speech sounds (Prince & Smolensky, 1993). The presence of more marked speech sounds (e.g., voiced stops) in a language implies the presence of less marked speech sounds (e.g., voiceless stops) in the markedness hierarchy but the presence of less marked speech sound does not ascertain the presence of the corresponding marked speech sound. Their studies from two decades of learnability project (Gierut, 2008) reveal that using more marked (or complex) stimuli for treating individuals with speech sound disorders leads to greater generalization across both marked (complex) and unmarked (simple) stimuli while using less marked stimuli only leads to generalization in unmarked (simple) but not marked (complex) stimuli. For example, Gierut (2007) treated subjects that produced affricates and fricatives incorrectly but stops correctly. They found that treatment with affricates that rank higher in the markedness hierarchy than fricatives and stops, led to generalization to both affricates and fricatives, while treatment with fricatives only led to generalization to fricatives but not to affricates. On the other hand, traditional-clinical approach towards this articulation profile would be to teach fricatives first as these are less marked (and simple) as compared to affricates. In speech therapy, traditional-clinical techniques range from the psycholinguistic (Pascoe et al., 2005) to "cycles" approach (Hodson & Paden, 1991; Mota et al., 2007) to perceptual approach (Morrisette et al., 2003;

Rvachew & Bernhardt, 2010; Rvachew & Nowak, 2001) to minimal pair training (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973). In traditional speech therapy, the therapist first exposes the children to the easiest/stimulable speech sounds also known as ear training or auditory bombardment. Listening to the therapist's articulation of the speech sounds, the children produce the target speech sounds and monitor their own productions. For example, with a child that incorrectly produces the sound [s], the therapist exposes the child to sound [s] in isolation followed by syllables (e.g., [si], [is], [isi]), words, phrases, sentences and finally to the conversational speech, in an increasing gradation of complexity. Further, the use of the target sounds in different contexts and word-positions are worked upon. Most of the therapy involves spanning through a hierarchy of difficulty levels starting from simpler sounds/word position/contexts to more difficult ones. So, these findings from the studies in speech and language learning reveal that there is little consensus on the extent of learning via complex and simple stimuli.

While the previous studies focusing on investigating the effect of complex and/or simple treatment have been conducted using behavioral techniques, as far as we are aware, there are no studies that have dealt with this research question from a neurophysiological standpoint. Electrophysiological findings have been found to bolster the behavioral findings in the learning-related studies (Kraus et al., 1995; Näätänen et al., 1993; Tremblay et al., 1997). It is known that speech and language experience shapes the automatic pre-attentive neural processing of speech sounds (Chandrasekaran, Krishnan, & Gandour, 2007; Cheour, Leppänen, & Kraus, 2000; Näätänen, Paavilainen, Rinne, & Alho, 2007; Tremblay et al., 1997, 1998). Pre-attentive neurophysiological measures have been found to show speech-learning-induced changes even before they are apparent in the behavior (Tremblay et al., 1998). Previous electrophysiological studies on speech-learning that reveal training-induced changes have either used same stimuli as in training (Kraus et al., 1995; Näätänen et al., 1993) or have used novel stimuli similar to the trained stimuli (Tremblay et al., 1997). With a pre-attentive neurophysiological measure as an index, it will be interesting to examine which training-type (complex or simple) leads to more training-induced neural plasticity. Most of the studies examining neural indicators of speech-learning have used mismatch negativity (MMN) that reflects pre-attentive discrimination of sounds (Csépe, Karmos, & Molnar, 1987; Giard, Perrin, Pernier, & Bouchet, 1990; Näätänen, Gaillard, & Mäntysalo, 1978; Sams, Paavilainen, Alho, & Näätänen, 1985), as an index for training-induced changes in auditory nervous system. Traditionally, MMN is evoked by presentation of a stimulus infrequently (rare) in a train of another stimulus (standard), in an oddball fashion (Näätänen et al., 1978). It is generally, a difference between the long latency event related potentials (peaks N1-P2-N2) elicited for rare and standard stimulus, emerging as a negativity between 100-300 msec. MMN has been extensively used for studying auditory discrimination abilities in language problems such as SLI (Bishop, 2007) and dyslexia (Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001). In treatment-related studies, MMN can be utilized to evaluate the improvement due to therapy or training by comparing its amplitude and/or latency from pre- to post-training.

It is evident that there is abundant literature from several scientific areas that support complex and simple theories. However, we find that a comprehensive study comparing the two theoretical viewpoints is lacking. Most of the previous findings stem from studies conducted on atypical population that could be heterogeneous at several levels. Additionally, we see that there is a lot of variability in the research designs, type of disorders studied, number of subjects, and outcome measures used across the studies in literature. Few studies that have been conducted to compare the two competing theories have mostly used single subject designs, chiefly criticized for a lack of stable baselines, difficulty determining the time intervals between probes and variability across the subjects (Diedrich, 1989; Rvachew & Nowak, 2001). Given these shortcomings, it becomes quite difficult to compare the magnitude of these findings in order to understand whether training with complex stimuli leads to more benefits or training with simple stimuli leads to more benefits.

In the current study, we aimed at conducting a behavioral and neurophysiological investigation using adult subjects in a two-group randomized controlled design with generalization to untreated stimuli as the outcome measure. We compared the performance of Cantonese-speaking adults trained on novel complex speech stimuli with those who were trained on novel simple speech stimuli in a sound-picture association task. The speech sounds that are more marked are considered complex while those that are less marked are consider simple. In the current study, we trained the subjects on Hindi dental and retroflex contrastive sounds (for example, /t̪a/-/ʈa/). Cantonese has alveolar voiceless plosives (similar to dental plosives /t̪a/) but do not have a retroflex counterpart (for example, /ʈa/) of the same. Thus, Cantonese speakers find it difficult to discriminate the contrast between dental and retroflex sounds. Furthermore, Cantonese lacks pre-voicing that appears in languages like Polish, French, Hindi, Hungarian, and Dutch. Apparently, the languages that have pre-voiced plosives also have voiceless plosives but the languages that have voiceless plosives do not necessarily have pre-voiced plosives. This suggests that pre-voiced plosives are typologically more marked and in an implicational relationship with voiceless plosives. So, in the current study, we used this markedness hierarchy as a vehicle to understand whether treatment with more marked/complex stimuli or treatment with less marked/simple stimuli leads to better learning outcomes. As generalization (to new tokens of stimuli) is considered as the most important indicator of improvement in training-induced studies, we predicted that the more efficacious learning technique (complex or simple) will induce more generalization to AX discrimination scores of untrained complex and simple contrasts. By extension, on the MMN measures, we predicted to see enhanced MMN amplitude for both complex and simple stimuli contrasts for the technique that turns out to be more efficacious.

4.2 Method

4.2.1 Participants

All participants (N = 120) in this study were native Hong Kong Cantonese speakers, studying at the Chinese University of Hong Kong. None of the participants reported any history of speech, language, hearing or neurological deficits. All had peripheral hearing sensitivity within 25 dB HL for the frequencies 0.5 to 4 kHz. Written informed consents were obtained from all participants prior to the experiments. The Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee approved the study. Out of the 120 subjects, (1) Sixty-four subjects participated in Experiment-1 that involved training and behavioral testing; (2) Thirty-two subjects participated in Experiment-2 that involved training, and behavioral and neurophysiological testing and; (3) Twenty-four subjects acted as control that didn't undergo any training.

4.2.2 Stimulus materials

Stimuli consisted of Hindi pre-voiced and voiceless dental and retroflex stop consonants /d̪, ɖ, t̪, ʈ/ produced with eight vowels (/a/, /i/, /u/, /o/, /e/, /ae/, /ə/, /ɒ/). The pre-voiced sound contrasts are typologically more marked/complex than, and in an implicational relationship with voiceless sound contrasts (Itô & Mester, 1998; Kager et al., 2007; Lombardi, 1999). These stimuli were produced by a phonetically-trained adult native speaker of Hindi in an acoustic-booth using a Shure SM10A microphone and Praat (Boersma & Weenink, 2010) with a sampling rate of 44.1 kHz and 16-bit sampling depth.

Acoustically, dental and retroflex stop sounds differ mainly in the shape of CV transition of the third formant i.e. falling for retroflex and rising for dental sounds. The naturally produced tokens were re-synthesized using Praat (Boersma & Weenink, 2010) to match the pitch, duration and intensity of the tokens such that the tokens occurring in pairs (e.g., / t̪a/ vs /ʈa/) only differed in the shape of the CV transition of the third formant keeping all other acoustic parameters the same.

We had five Hindi judges to confirm the validity of our stimuli. They scored 93-97% on an identification task of these sounds. The stimuli pairs were then assigned to two sets – Set-A and Set-B with each set having 4 pairs each of pre-voiced and voiceless dental-retroflex CV stimuli. Set-A consisted of sounds /d̪, ɖ, t̪, ʈ/ in /Ca/, /Ci/, /Cu/, /Co/ context while Set-B had these sounds in /Ce/, /Cae/, /Cə/, /Cɒ/ contexts.

4.2.3 Procedure

4.2.3.1 Experiment-1 (Behavioral)

Sixty-four subjects participated in Experiment-1 out of which 32 subjects (mean age = 24.3 y, 8 males) were tested on Set-A and trained on Set-B while the other 32 (mean age = 23.6 y, 12 males) subjects were tested on Set-B and trained on Set-A. Out of 32 subjects trained on each set, 16 subjects) were trained on complex stimuli (pre-voiced dental-retroflex) while the other 16 subjects were trained on simple stimuli (voiceless dental-retroflex).

4.2.3.1.1 Evaluation

Pre- and Post-training evaluation involved AX discrimination task where the subjects were presented pre-voiced and voiceless dental-retroflex contrast pairs and they were required to press the appropriate button to indicate "same" or "different". Two practice trials (with 2 repetitions), different from the experimental items were provided to the participants to familiarize them with the task. Participants were presented with a total of 128 stimulus pairs (2 contrast-type (pre-voiced/voiceless) × 4 token pairs × 4 repetitions × 2 "identical" sequences × 2 "different" sequences) with an interstimulus interval of 1000 msec.

4.2.3.1.2 Training

Training involved teaching the participants in a pseudoword-picture association task (Antoniou & Wong, 2016; Chen et al., 2015; Wong & Perrachione, 2007). In each training session, 64 stimuli (2 contrast-type (dental/retroflex) × 4 tokens × 8 repetitions) were played out simultaneously with pictures at an interstimulus interval of 2000 msec. After all the 64 stimuli were played out, the participants were asked to identify the correct picture for the pseudowords (that they just learned) in an 8 alternate-forced-choice (AFC) identification task. The order of presentation of stimuli were randomized in both training and identification tasks.

4.2.3.2 Experiment-2 (Behavioral and Neurophysiological)

Thirty-two novel subjects participated in Experiment-2 who were tested on Set-B and trained on Set-A. Similar to Experiment-1, out of 32 subjects, 16 subjects (mean age = 23,8 y, 5 males) were trained on complex stimuli while the other 16 subjects (mean age = 24.1 y, 6 males) were trained on simple stimuli.

4.2.3.2.1 Behavioral Evaluation

Same as in Experiment-1 (Section 2.3.1.1.)

4.2.3.2.2 Electrophysiological Testing

We collected MMN data from 1000 trials in an oddball paradigm (Standard : Rare :: 80 : 20) for the complex and simple stimuli contrasts. The order of block presentation (complex or simple) were counterbalanced across the subjects as well as across pre- and post-training testing for each subject. The stimuli were presented binaurally at an intensity of 80 dB SPL via Compumedics 10Ω insert earphones at an interstimulus interval of 800 msec using the Gentask module of STIM2 (Compumedics, USA). Participants watched a silent movie during the recording and were instructed to ignore the sound stimuli presented to their ears. Continuous electrophysiological data were collected using a 5-electrode montage with Cz-M1-M2 as the active electrodes, CPz as reference and lower forehead as ground, with the inter-electrode impedances maintained at ≤ 1 kΩ. The data were collected at a sampling rate of 1000 Hz using a Synamps RT amplifier (Compumedics, El Paso, TX).

Offline data pre-processing was conducted using customized EEGLAB and ERPLAB scripts on MATLAB (2016a). During the analysis, the data were downsampled to 500 Hz, artifact rejected (± 85 µV), filtered (1-30 Hz), epoched (-100 to 500 msec), baseline-corrected, and averaged to obtain the MMN waveforms. Three MMN recordings with more than 15% of rejected trials (i.e., > 150 rejections) were removed and not included in further analyses.

4.2.3.2.3 Training

Same as in Experiment-1 (Section 2.3.1.1.)

4.2.3.3 No-training Control

The subjects (n = 24) in this group were not given any training. They were tested on AX discrimination task on the first and fifth day with no training. Twelve subjects were tested with Set-A while the other 12 subjects were tested with Set-B.

4.3 Results

4.3.1 Experiment-1

4.3.1.1 Training

At the end of each training session, as the subjects identified pictures associated with the words that they just learned, we got their learning trajectory across the five sessions. Overall, we see that the subjects trained either on complex or simple stimuli across the five sessions, learned to a similar degree. The learning curves show that on an average, the participants started with around 40-50% sound-picture association on the first session and improved to around 70-75% on their fifth session. Further, both the sets A (Figure 9(A)) and B (Figure 9(B)) were found to be similar on subjects' performance.

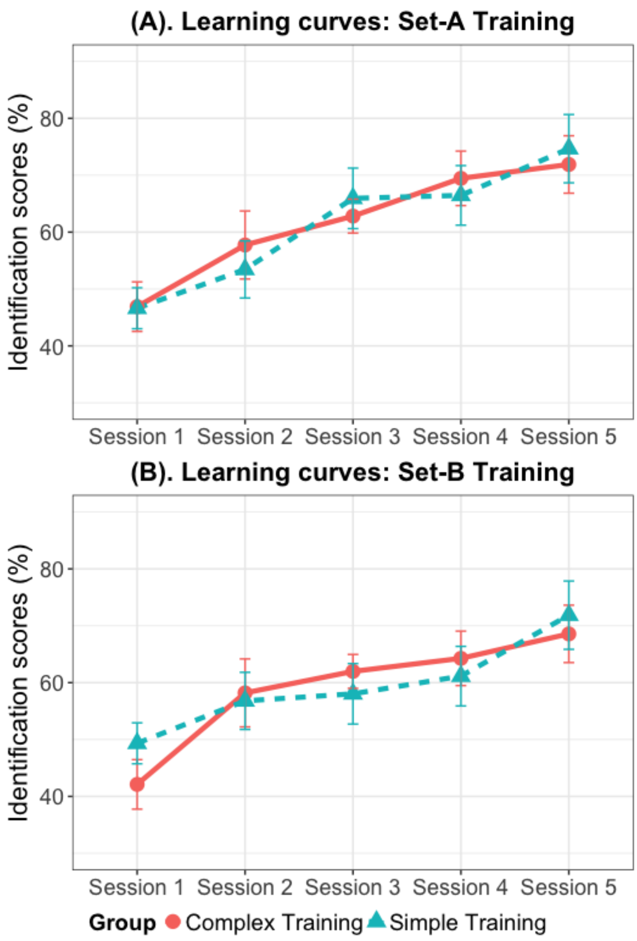

Figure 9. Learning curves for subjects trained on complex and simple stimuli for (A) Set-A; and (B) Set-B. (Error bars = ±SEM)

4.3.1.2 Evaluation

The participant groups were compared on AX discrimination of complex and simple stimuli contrasts, before (Pre) and after the training (Post). For both the sets (A and B) of stimuli, we found that the group trained with complex stimuli improved on AX discrimination abilities of both complex and simple stimuli contrasts (Figures 10(A) and 10(C)) while the group trained with simple stimuli contrasts improved on AX discrimination abilities of only simple stimuli but not the complex ones (Figures 10(B) and 10(D)).

Set A: In the complex training group, we found a main effect of stimuli ($F(1, 15) = 5.53$, $p = .033$) and a main effect of evaluation ($F(1, 15) = 88.93$, $p = .000$) but no significant interaction between stimuli and evaluation ($F(1, 15) = 2.66$, $p = .123$) that implies that following the complex training, the scores from pre to post training evaluation changed for both complex and simple stimuli. For the simple training group, we found main effects of stimuli ($F(1, 15) = 12.73$, $p = .003$) and evaluation ($F(1, 15) = 35.29$, $p = .000$) and a significant interaction between stimuli and evaluation $F(1, 15) = 46.71$, $p = .000$) that implies that following the simple training, the scores from pre to post training evaluation changed only for simple stimuli but not for complex stimuli.

Set B: In the complex training group, we found a main effect of stimuli ($F(1, 15) = 12.70$, $p = .003$) and main effect of evaluation ($F(1, 15) = 113.85$, $p = .000$) and a significant interaction between stimuli and evaluation ($F(1, 15) = 6.48$, $p = .022$). For the simple training group, we found main effects of stimuli ($F(1, 15) = 49.08$, $p = .000$) and evaluation ($F(1, 15) = 11.33$, $p = .004$) and a significant interaction between stimuli and evaluation $F(1, 15) = 36.46$, $p = .000$) that implies that following the simple training, the scores from pre to post training evaluation changed only for simple stimuli but not for complex stimuli.

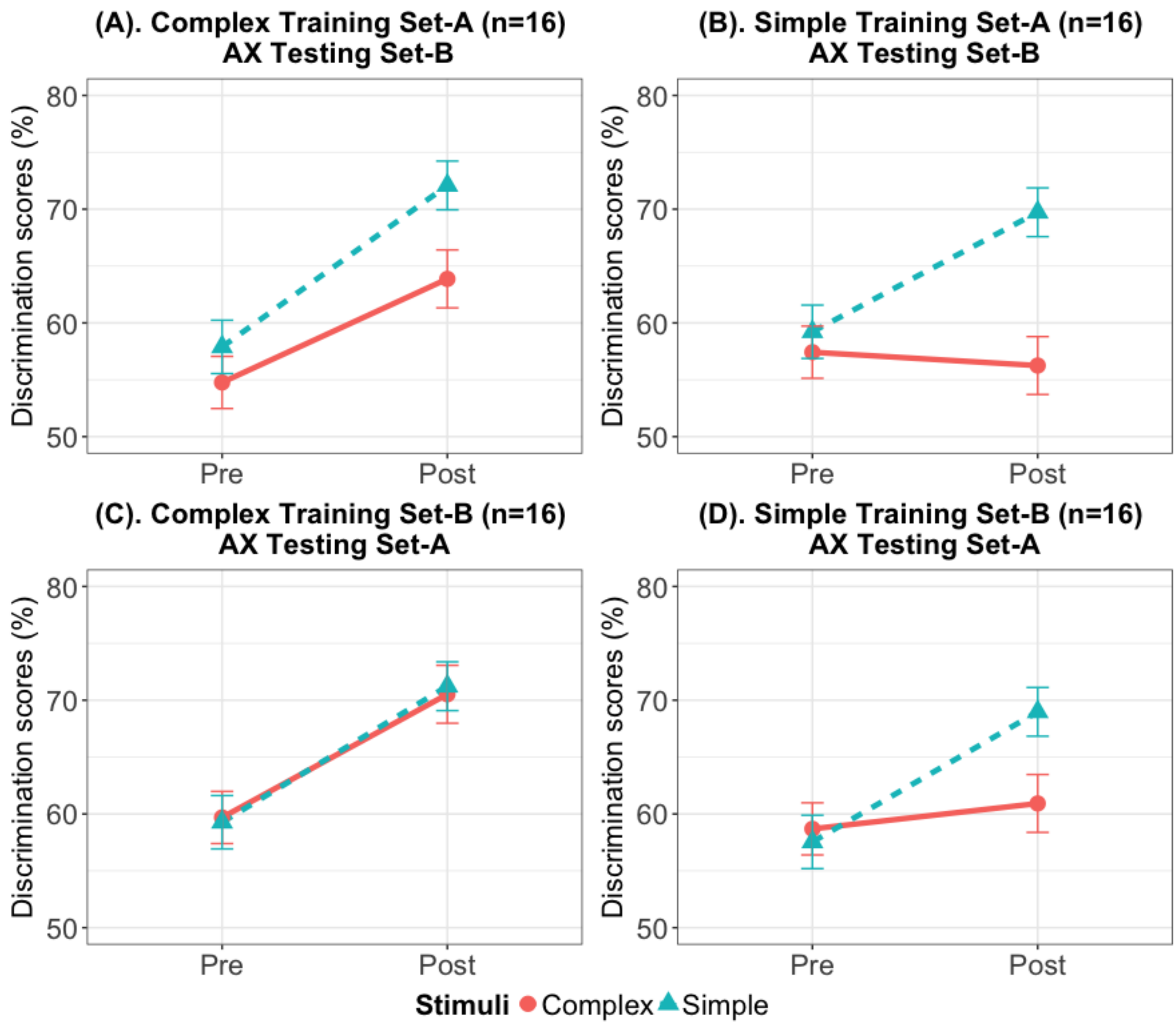

Figure 10. Discrimination scores for AX testing for subjects: (A) Trained on complex stimuli of Set-A, tested on both complex and simple stimuli of Set-B; (B) Trained on simple stimuli of Set-A, tested on both complex and simple stimuli of Set-B; (C) Trained on complex stimuli of Set-B, tested on both complex and simple stimuli of Set-A; and (D) Trained on simple stimuli of Set-B, tested on both complex and simple stimuli of Set-B. (Error bars = ±SEM)

Overall, the findings from this experiment reveal that those subjects who were trained with complex stimuli improved on the perception of both complex and simple stimuli. On the other hand, those subjects who were trained with simple stimuli only improved on the perception of simple stimuli but not complex stimuli.

4.3.2 Experiment-2

4.3.2.1 Behavioral

4.3.2.1.1 Training

These subjects were trained on Set-A. Similar to the findings from Experiment-1, the data from this experiment show that the group trained on complex and simple stimuli achieved similar level of learning across the five sessions of training. They began at around 40-45% in their first session and learned up to 70-75% (Figure 11).

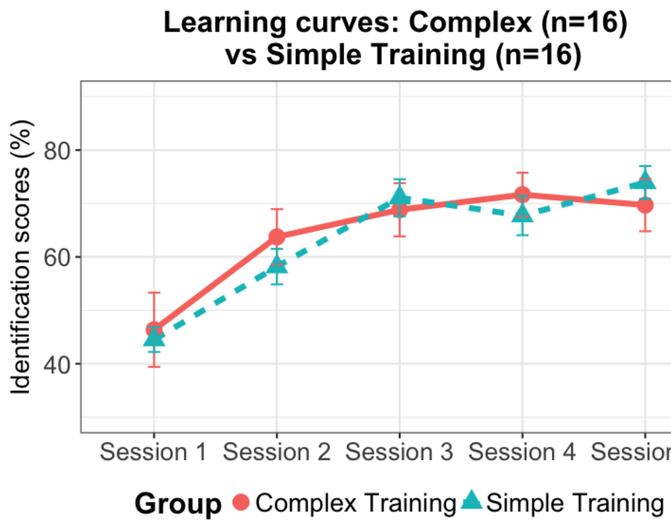

Figure 11. Learning curves for subjects trained on complex and simple stimuli for Set-A. (Error bars = ±SEM)

4.3.2.1.2 Evaluation

The results for AX discrimination were similar to Experiment-1. The group that was trained with complex stimuli showed improvement on both complex and simple stimuli while the groups trained on simplex stimuli only showed improvement in simple but not complex stimuli. For the group trained on complex stimuli, there was a main effect of stimuli ($F(1, 15) = 9.47$, $p = .008$) and evaluation ($F(1, 15) = 23.36$, $p = .000$) but no significant interaction between stimuli and evaluation ($F(1, 15) = 1$, $p = .333$) (Figure 12(A)). On the other hand, for the group trained on simple stimuli, there were main effects of stimuli ($F(1, 15) = 17.92$, $p = .001$) and evaluation ($F(1, 15) = 14.16$, $p = .002$) and a significant interaction between stimuli and evaluation ($F(1, 15) = 7.44$, $p = .016$) (Figure 12(B)).

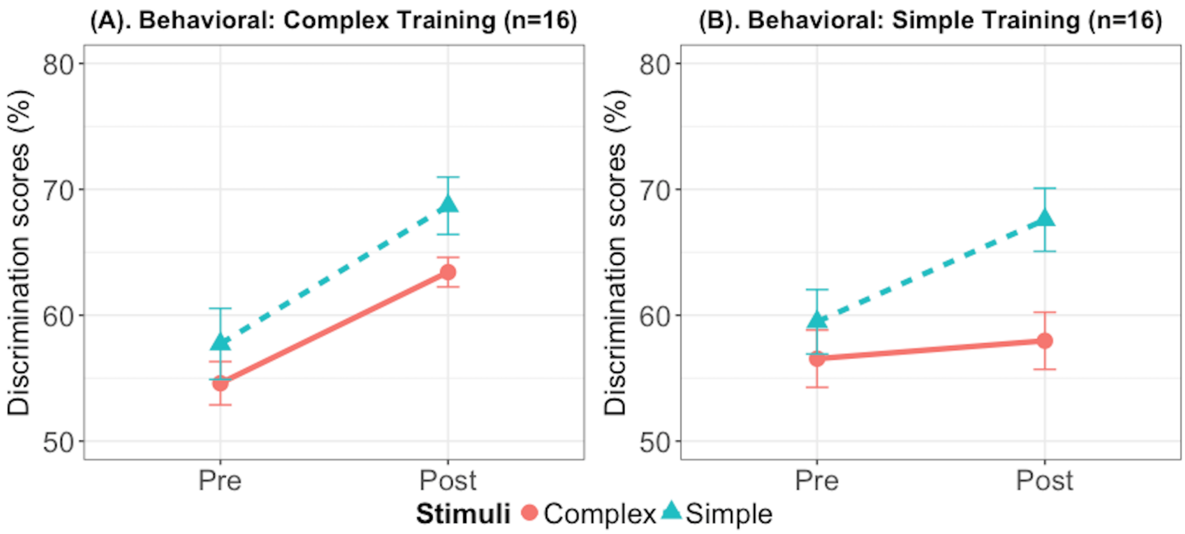

Figure 12. Discrimination scores for AX testing for subjects (A) Trained on complex stimuli of Set-A, tested on both complex and simple stimuli of Set-B; (B) Trained on simple stimuli of Set-A, tested on both complex and simple stimuli of Set-B. (Error bars = ±SEM)

4.3.2.2 Individual differences

Further, we combined our behavioral data from Experiments 1(n = 64) and 2 (n = 32) to understand the individual variability in learning success. Overall, we found large individual differences in the improvement following complex training on complex stimuli (range = -3.13% to 31.25%) and simple stimuli (range = -7.81% to 34.38%) (Figure 13(A)). Similarly, we found individual differences in the improvement following simple training on complex stimuli (-9.38% to 9.38%) and simple stimuli (-17.18% to 26.56%) (Figure 13(B)). Most of the subjects (87%; n = 42) trained with complex training improved on both complex and simple stimuli while among the subjects trained with simple training, more than half (52%; n = 25) improved only on simple but not on complex stimuli. Additionally, only 8.33% of the subjects (n =4) who were treated with complex stimuli did not generalize to simple stimuli while 39.58% of the subjects (n = 19) who were treated with simple stimuli did not generalize to complex stimuli.

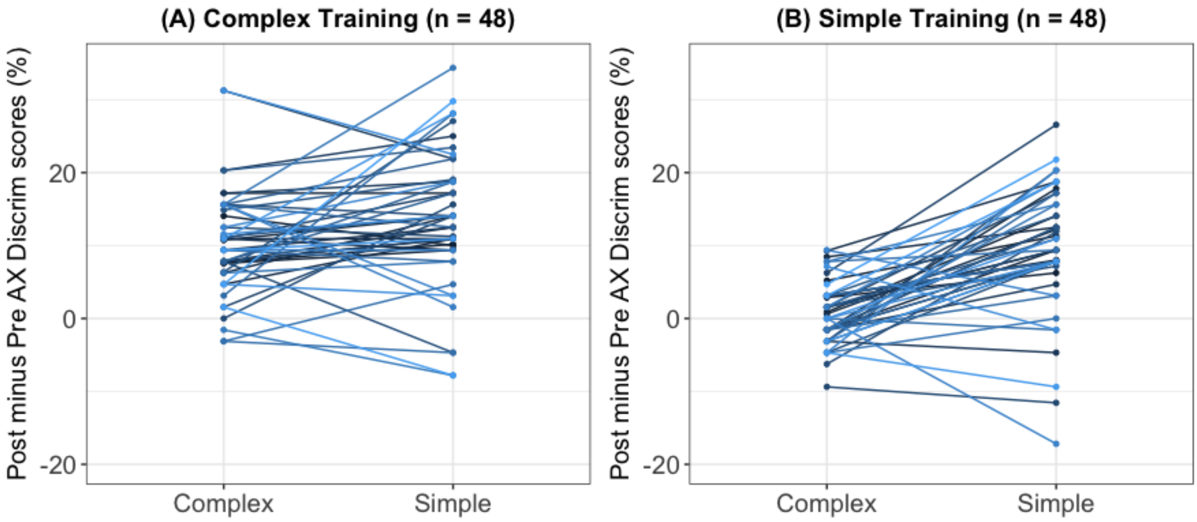

Figure 13. Individual improvement (Post-training minus Pre-training Scores (%)) for complex and simple stimuli for subjects trained with (A) Complex Training; and (B) Simple Training.

More specifically, we found that the subjects trained with simple training (n = 48) were more homogenous in their trend of improvement i.e. 90% of the subjects (n = 43) improved more on simple stimuli than complex stimuli while only10% (n = 5) improved more on complex than simple stimuli (Figure 14(B)). On the other hand, the subjects (n = 48) trained with complex stimuli showed relatively more variability in their improvement trend i.e. while 48% of the subjects (n = 23) showed more improvement on simple than complex stimuli, there were 33% of the subjects (n = 16) who showed equivalent improvement on both complex and simple stimuli followed by 11% of the subjects (n = 5) who showed more improvement on complex than simple stimuli followed by 8% of the subjects (n = 4) who showed better improvement scores on complex but not on simple stimuli (Figure 14(A)).

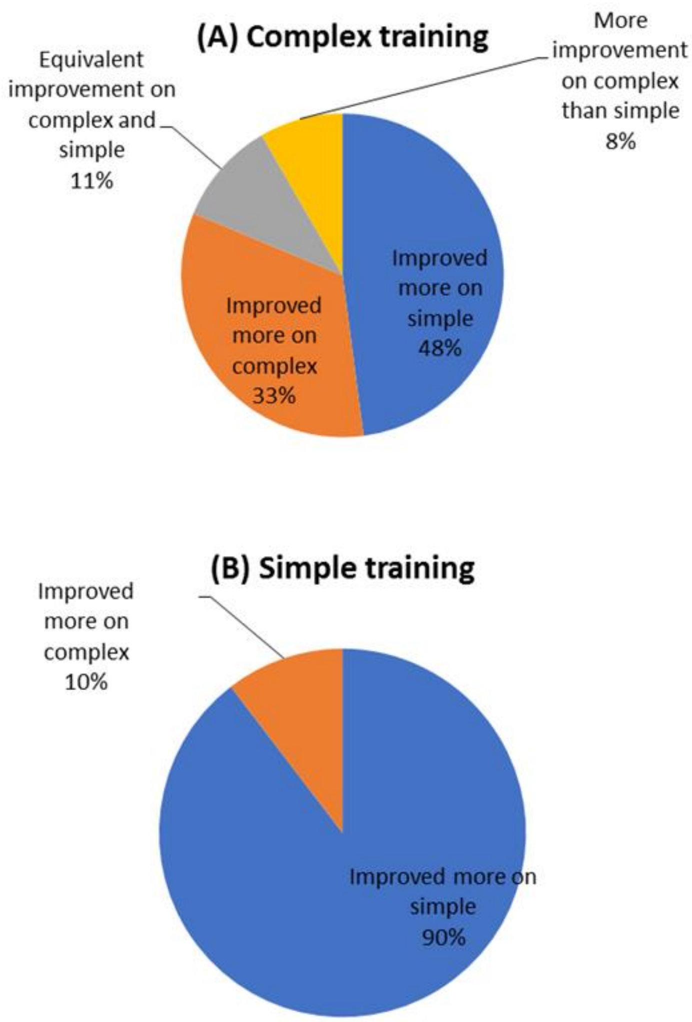

Figure 14. Distribution of the subjects across (A) Complex training; and (B) Simple training. Overall, most of the subjects trained with simple stimuli led to more improvement on simple stimuli while the subjects trained with complex stimuli showed more variable changes following training.

4.3.2.3 Electrophysiological evaluation

On the pre-processed MMN data, we compared mean amplitude between the latency of 100-300 msec. Similar to the behavioral data, we also found that there was a change in MMN following training. In the shaded time-windows (Figures 15 and 16), the gap between the red and blue lines represents the MMN, which is their ability to pre-attentively discriminate the sounds in the contrast. The group trained with complex stimuli showed that there were changes in MMN amplitude for both complex and simple stimuli (Figures 17(A) and 15(A-D)) while the group trained with simple stimuli showed improvement in only simple stimuli and not the complex ones (Figures 17(B) and 16(A-D)).

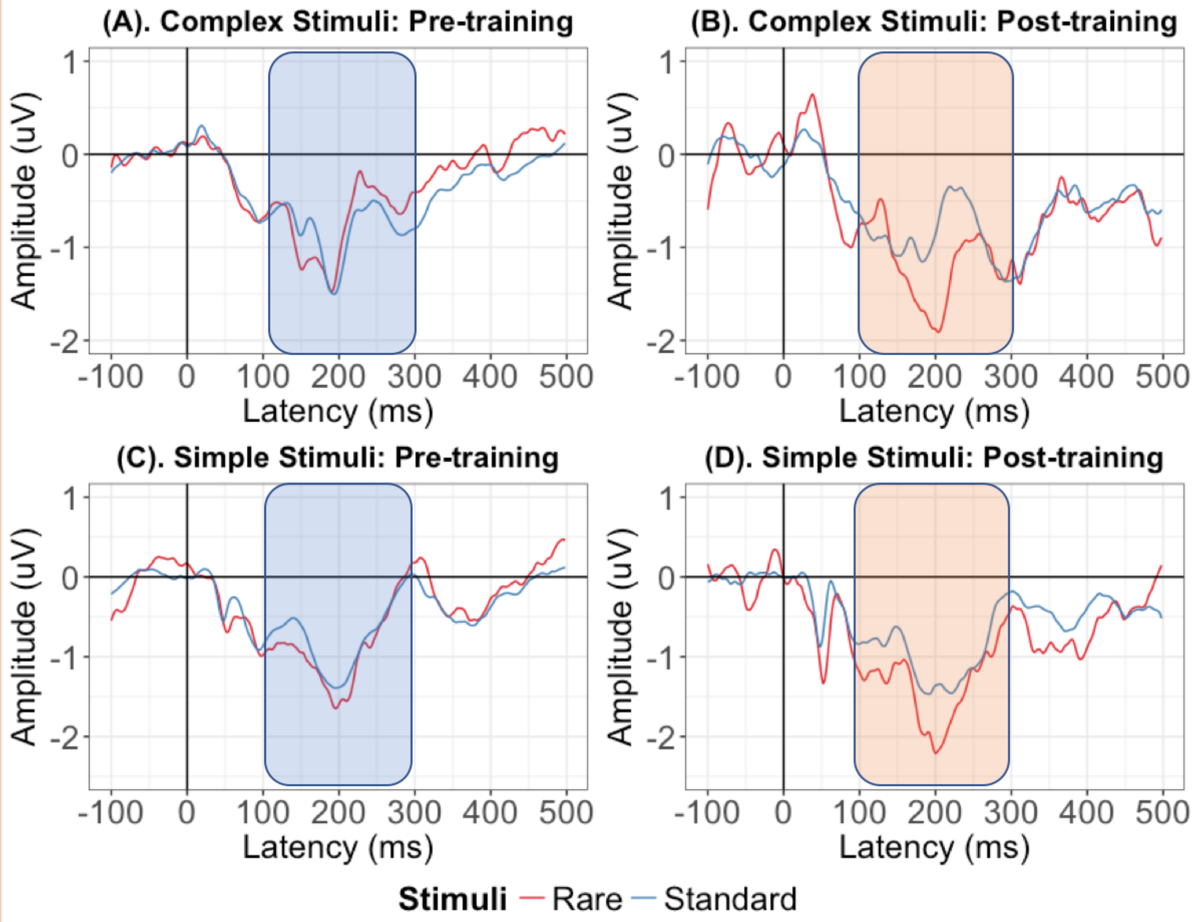

Figure 15. MMN waveforms for subjects trained on complex stimuli and tested on both complex and simple stimuli; (A) Pre-training MMN for complex stimuli; (B) Post-training MMN for complex stimuli; (C) Pre-training MMN for simple stimuli; and (D) Post-training MMN for simple stimuli.

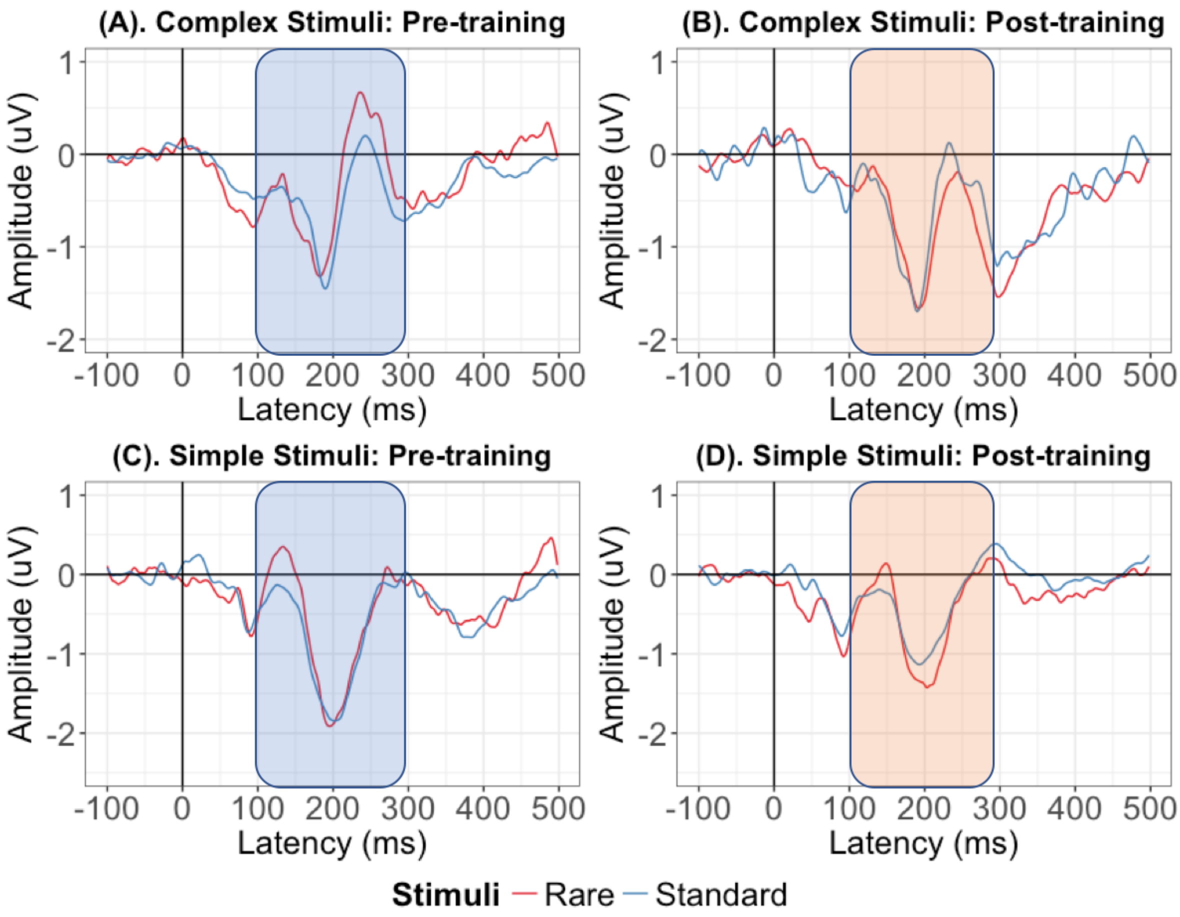

Figure 16. MMN waveforms for subjects trained on simple stimuli and tested on both complex and simple stimuli; (A) Pre-training MMN for complex stimuli; (B) Post-training MMN for complex stimuli; (C) Pre-training MMN for simple stimuli; and (D) Post-training MMN for simple stimuli.

For the group trained on complex stimuli, there was a main effect of evaluation ($F(1, 15) = 11.01$, $p = .005$), no main effect of stimuli ($F(1, 15) = .955$, $p = .334$), and no significant interaction between stimuli and evaluation ($F(1, 15) = .55$, $p = .47$). On the other hand, for the group trained on simple stimuli, there were no main effects of stimuli ($F(1, 15) =.2$, $p = .661$) or evaluation ($F(1, 15) = .828$, $p = .337$) but a significant interaction between stimuli and evaluation ($F(1, 15) = 12.072$, $p = .004$).

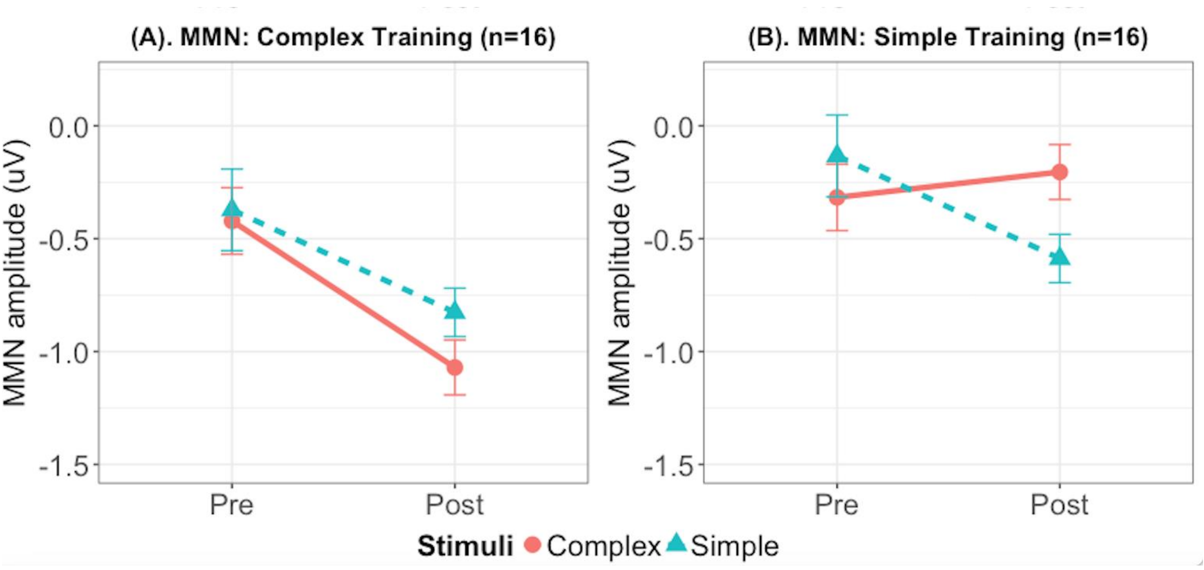

Figure 17. MMN amplitude for subjects (A) Trained on complex stimuli of Set-A, tested on both complex and simple stimuli of Set-B; (B) Trained on simple stimuli of Set-A, tested on both complex and simple stimuli of Set-B. (Error bars = ±SEM)

4.3.3 No-training Control

For both the sets, there were no significant differences between the evaluations on the first and fifth day. For Set-A, there were no main effects of stimuli ($F(1, 11) = 1.38$, $p = .265$) and evaluation ($F(1, 11) = 4.48$, $p =.16$) and no significant interaction of stimuli and evaluation ($F(1, 11) = .016$, $p = .9$). Similarly, for Set-B, there were no main effects of stimuli ($F(1, 11) = .357$, $p =.562$) and evaluation ($F(1, 11) = .883$, $p =.367$) and no significant interaction of stimuli and evaluation ($F(1, 11) = 3.59$, $p = .084$).

4.4 Discussion

In the current study, we found that learning with complex input leads to improvement in the perception of untreated complex and simple speech sound contrasts while training with simple input only leads to improvement in perception of simple sound contrasts but did not generalize to the complex sound contrasts. In Experiment-1, we found that the subjects who were trained with pre-voiced dental and retroflex (complex) sound-picture association task, improved on the discrimination scores of both pre-voiced and voiceless dental-retroflex contrasts while the subjects who learned voiceless dental and retroflex sounds (simple) in a sound-picture association task, improved only on the discrimination scores of voiceless dental-retroflex contrasts but not the pre-voiced dental-retroflex sounds. In Experiment-2, we found that there was more change in MMN amplitude from pre- to post-training for both complex and simple contrast MMN when training for complex stimuli was provided while there was only change in MMN for simple but not complex contrasts when training for simple sounds was provided. Additionally, behavioral findings in Experiment-2 replicated the findings of Experiment-1. Overall, the current behavioral and electrophysiological findings are consistent with the postulates of the complex-learning theories that suggest that complexity induces widespread learning and generalization by exposing underlying simpler structures.

Additionally, we examined our combined behavioral data from Experiments 1 and 2 to investigate the individual differences in improvement in perception of complex and simple stimuli following the training paradigm. Overall, we found a considerable variability in learning success, which is in agreement with the previous studies on adult second language learning (Birdsong, 1999; Ettlinger, Bradlow, & Wong, 2014; Golestani & Zatorre, 2009; Iverson, Hazan, & Bannister, 2005; Wong, Morgan-Short, Ettlinger, & Zheng, 2012; Wong & Perrachione, 2007). Based on findings from the previous studies (Ettlinger et al. 2014; Wong et al., 2012), the current findings on individual differences in learning success following training can be speculated to be a result of variability in the domain-general cognitive functions such as declarative and procedural memory (Ettlinger et al., 2014) that might have an underlying genetic basis (Wong et al., 2012).

The neural findings from the current study are consistent with the previous findings (Chandrasekaran et al., 2007; Kraus et al., 1995; Tremblay et al., 1997, 1998) that reveal neural plasticity of the pre-attentive auditory processing induced by experiential learning. The current findings are also consistent with the findings of Tremblay et al. (1997) who revealed that training-induced plasticity not only occurs for the trained stimuli but also generalizes to the novel stimuli similar to the trained stimuli. Further, the current findings revealed that the training-induced plasticity also follows the similar implicational hierarchy as in behavioral data, further reinforcing the behavioral findings of this study.

Our findings are in agreement with studies from several scientific domains including cognitive development (Piaget, 1952; Kuhn, 1972), motor skill acquisition (Schmidt & Lee, 1989; Wulf & Shea, 2002), computational modelling (Elman 1993; Rohde & Plaut, 1999; Plaut, 1996), second language learning (Eckman et al., 1988), phonological disorders (Gierut, 2007; Rvachew, 2005), language disorders (Kiran, 2007; Thompson & Shapiro, 2007), gaming (Özgün & Barlas, 2013), and math learning (Yao, 1989), that support the usefulness of using complex over simple stimuli to obtain more enhanced improvement. The current findings support the findings of Kuhn (1972) who studied the performance of children taught with the stimuli based on Piaget's (1952) six stages of cognitive development. Piaget's stages are based on children's ability to begin with most concrete or stable concepts extending to more abstract concepts in the later stages. Kuhn (1972) compared the children who were taught with stimuli from their baseline condition (subset) and those who were taught with structures from more advanced stages (superset). It was found that the children who were instructed with material from their baseline of cognitive development, did not show improvement on the complex stages of operational thinking while the children taught with advanced stages were able to generalize to the stimuli from advanced as well as subordinate stages. The current findings are also in agreement with computational modelling studies (Plaut, 1996; Rohde & Plaut, 1999) where it was found that exposing a system to the whole pseudogrammar rather than smaller steps led to better learning outcomes. These findings are also consistent with gaming studies (James & Stephen, 1994) that reveal that experience of harder levels of the game directly lead to more efficient outcomes as compared to starting from easier levels and progressing to harder ones. Additionally, the current findings are also in agreement with studies in math (Yao, 1989), and motor skill acquisition (Schmidt & Lee, 1989) that support the use of complex input in obtaining more efficacious learning outcomes. Looking at the convergence of findings of the current study on speech-learning and the findings from several other disciplines, it can be speculated that complexity could be a domain-general property. However, the way complexity can be defined and implemented in each domain may be specific to that domain. For example, complexity in speech sounds can be defined by markedness hierarchy while in gaming it can be defined by the levels of the game.

In the context of speech sound training, the current findings are consistent with the findings of the treatment studies (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) on children with speech sound disorders that suggest the efficacy of complex input towards the treatment of children with speech sound disorders. The current findings align well with the postulates of learnability theory within the context of universal grammar (Wexler, 1982; Wexler & Culicover, 1980) that postulates the concept of innate complexity, in the current study, complex input turned out to be more efficient than the simple input as complexity in input can trigger an overall development in a rule-governed manner while the simple input cannot trigger this extensive development, and is limited to development of structures of equivalent or lesser complexity.

The current findings on learning may have potential implications in the field of education and rehabilitation. Traditionally, teachers have proposed that teaching easier concepts first leads to better foundation and building on them leads to better learning, leading to better results. However, in the light of the current findings, it can be speculated that teaching complex concepts first leads to enhanced improvement. Learning complex concepts leads to extended generalization to other concepts of equivalent and/or lesser complexity, and is cost and time effective. In the field of communication disorders, learning via complex structures have far-reaching implications. The current findings, especially, have direct potential implications towards treatment of children and adults with speech sound disorders. Speech sound disorder in the childhood has extensive effects on the quality of education and living that one attains later in the life. From a financial standpoint, in healthcare industry, it is needed to implement more efficient techniques. Studies in treatment of syntactic deficits in aphasia (Thompson et al., 2003; Thompson et al., 1998) report a great disparity between the time taken by complex vs simple technique. Thompson et al. (1998), in their study, found that treatment with complex syntactic structures required 13 sessions to meet the criterion (i.e., 80% correct productions), whereas treatment with simple structures required an average of 34 sessions. Similarly, Thompson et al. (2003) found that participants that were treated with complex structures required just 12 sessions while those treated with simple structures needed 28 sessions.

4.5 Future directions

The current findings have used markedness hierarchy as a vehicle to define complexity hierarchy in speech sounds. In order to further ascertain the domain-general characteristics of complexity, future studies could be conducted using a similar research design but with different ways of defining complexity in speech sounds. For example, training with two new sounds could be considered a complex condition while training with one new sound considered as simple condition. If findings with such stimuli converge with the findings from the current study, it would be confirmatory of the domain-general aspects of complexity.

Chapter 5

Complexity drives speech sound development: Evidence from speech therapy

5.1 Introduction

Whether speech and language acquisition is driven by complex input or by simple input remains a controversial topic. Complexity in speech sounds can be gauged by phonological markedness (Dinnsen, 2008). Speech sounds that are phonologically marked can be considered complex while the speech sounds that are phonologically unmarked can be considered simple. The notion that complex sounds are needed to drive speech sound development (hereafter, *complex theories*) has its foundations in the complexity-based linguistic theories (e.g., generative phonology, natural phonology, and optimality theory) while the notion that exposure to simple sounds first is more important to promote speech sound development (hereafter, *simple theories*) stems from traditional theories (e.g., behaviorist theories, connectionist view, dynamic systems theory) of speech sound development. To experimentally investigate the psychological reality of these theories, treatment-based studies could provide an excellent opportunity, as they allow selective manipulation of the treatment variables (Barlow & Gierut, 1999) to observe effects in atypical population. In the past, there are only a few treatment-based case reports (Dinnsen, 2008; Dinnsen & Elbert, 1984; Gierut, 1989; Powell & Elbert, 1984) that have compared the two sets of theories. Moreover, these case reports are limited to children from English-speaking homes. In the current study, we compared these two competing theories on speech sound development by comparing the effects of complex treatment and simple treatment on children with speech sound disorders from Cantonese-speaking homes. By conducting a study in children who speak Cantonese, a language with a relatively simple syllable structure, we can further shed light on the efficacy of these therapy-types and further contribute towards broadening the existing empirical base.

Classically, the concept of markedness puts forth a *marked/unmarked* dichotomy where unmarked elements are those that are more natural, simpler, common, and general while marked elements are those that are less natural, less common, more complex, and more specific. Markedness hierarchy in phonology defines implicational relationships, both typologically, and in acquisition (Jakobson, 1968). The order of elements in the implicational hierarchy defines their status in terms of complexity. The presence of a more marked sound in a language implies the presence of corresponding less marked sound. So, the more marked sound (in a markedness hierarchy) is considered more complex as compared to the less marked sound. For example, voiced stops (/b/, /d/, /g/) being more marked imply voiceless stops (/p/, /t/, /k/). Markedness implicational relationship can also be illustrated with an example from syllable structure. It is largely agreed that CV syllables are unmarked with respect to syllable shape (e.g., Blevins, 1996; Clements, 1990; Clements & Keyser, 1983). There are languages that allow CV syllables (with simple onsets) but do not allow CCV syllables (with complex onsets) (e.g., Hawaiian; Elbert & Pukui, 1979). On the other hand, there are languages that allow CCV syllables (e.g., clusters) as well as CV syllables (e.g., English). However, there are no languages that allow complex onsets, but no CV syllables. This observation illustrates that the presence of a marked or more complex structure in a language (e.g., complex onsets in English) implies the presence of an unmarked or simple structure (e.g., CV syllables in English) but not *vice versa* (e.g., absence of clusters in Hawaiian with the presence of CV syllables) (Levelt & Van de Vijver, 2004). In child phonology, unmarked or simple structures (e.g. stops) occur more frequently than marked or complex structures. This is mainly because children tend to simplify complex sounds (more marked) to simpler ones (unmarked). However, as they grow, more marked or complex structures emerge in their phonological system.

Complex theories support the importance of complex input in promoting acquisition of both complex and simple speech sounds. Complex stimuli along with development of complex structures promotes development of simpler structures, by exposing a child to surface forms that cannot be generated by their internal grammar, triggering improvement of other structures with equivalent or lesser complexity, leading to an overall change in their language system (Baker & Williams, 2010; Gierut, 1989, 2001; Morrisette et al., 2003; Powell et al., 1991). Optimality Theory (OT; Prince & Smolensky, 1993), one of the complexity theories, postulates the existence of universal markedness and faithfulness constraints that play a central role in accounting for the phonological acquisition. In OT, hierarchical ranking of these constraints governs the surface representation based on a set of underlying representations (i.e., a lexicon). Markedness constraints evaluate surface representations only and penalize them for certain configurations. E.g., *VOI penalizes voicing. On the other hand, faithfulness constraints consider both the underlying and surface levels and their effect is that the surface form is similar to the underlying form and there are no changes. E.g., MAX penalizes deletion, thus ensuring that the underlying form is retained in the surface form. Though these constraints are universal, their rankings differ across languages, making these languages typologically different. OT accounts for phonological acquisition based on universal constraints and their language-specific input-driven re-ranking during development. These set of constraints align themselves in implicational hierarchy that drive acquisition. For example, the markedness hierarchy of *ComplexCoda >> *Coda because of which if a child acquires more complex or marked [CVCC] then simple or unmarked [CVC] is implied. Further, the constraint rankings may also differ within a language at least when comparing typically developing children and those with phonological disorders (Dinnsen, 2008). In a child acquiring language, markedness constraints outrank the faithfulness constraints in the initial state (Smolensky, 1996), thus necessitating acquisition via constraint re-ranking.

On the other hand, traditional or simple-based theories postulate that exposure to simple stimuli first is the key to trigger development. The traditional theories that support the importance of simple stimuli first include behaviorist theories (Skinner, 1957), scaffolding (see Piaget, 1962; Vygotsky, 1962), dynamic systems theory (De Bot et al., 2007; Rvachew & Bernhardt, 2010) and the connectionist models of language acquisition (Elman, 1993). Behaviorism (Skinner, 1957; Watson, 1913) is focused on describing the behaviors that can be observed in response to stimuli. Within the scope of speech sound development, behaviorist theories stress upon the environmental factors (stimuli) that could predict overt verbal behaviors (responses). Behaviorist theories suggest that the sounds that are simple and easy to discriminate are learned first (Olmsted, 1971), mainly via imitation, followed by the acquisition of difficult sounds. Similarly, computational modelling studies based on connectionist models (Elman, 1993) provide evidence for the importance of starting with simpler structures than starting with complex structures towards development. According to these theories, it is the interaction of the course of maturation and acquisition of language that requires simple input in the initial stages, to promote the development of complex structures later (Elman, 1993). Starting small with gradually increasing complexity is proposedly more advantageous to the acquisition of language as compared to exposure to the complex adult-like forms directly (Plunkett & Marchman, 1993). Quite recently, dynamic systems theory has been used in the study of speech sound development (De Bot et al., 2007; Rvachew & Bernhardt, 2010), that suggests that stability of subcomponents is of utmost importance for the development to take place. Interaction of the subcomponents leads to emergence of continuities and discontinuities in the system that leads to development of a given behavior.

Dynamic systems theory suggests that for development of speech sounds, stimulability of simpler speech sounds is needed (Bernhardt, 1992; Rvachew & Bernhardt, 2010). For instance, in a child with improper articulation of onset clusters, stimulability of less complex sounds (such as stops) is needed to direct the way for development of complex sounds. In a similar vein to the behaviorist theories, dynamic systems theory suggests that for learning complex speech sounds, strengthening of correct articulation of simpler speech sounds via feedback and reinforcement is necessary (Rvachew & Bernhardt, 2010).

5.1.1 Treatment studies

Traditional-clinical approaches, based on the traditional theories of speech sound development, include the traditional speech therapy (Van Riper & Emerick, 1984), the "cycles" approach (Hodson & Paden, 1991; Mota et al., 2007), minimal pair training (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973), psycholinguistic approach (Pascoe et al., 2005), and perceptual approach (Morrisette et al., 2003; Rvachew & Bernhardt, 2010; Rvachew & Nowak, 2001). Traditionally, speech therapy begins with ear training or auditory bombardment with the most stimulable or least problematic sounds for children with speech sound disorders. When exposed to the model articulation of the sounds repetitively, the child is given an environment to monitor his/her own articulation. For example, if a child's phonological profile depicts problems in articulation of the sound [d], then the therapist starts with exposure of the child to sound [d] in isolation first, followed by expanding to syllables in CV, VC, and CVC contexts. Once criterion accuracy is achieved at this stage, the therapist moves the child to higher stages where training for words, phrases, and sentences takes place. Basically, the therapy involves a gradual expansion of the child's articulation abilities from most easy to most difficult or complex stimuli. Another traditional-clinical approach is the *cycles* approach (Hodson &

Paden, 1991) where a therapist first examines the whole range of errors, contexts and error patterns (if any) in the phonological profile of the child with speech sound disorder. Following the identification of error patterns, the treatment begins with the sounds that are the most stimulable and easiest for the child. However, the therapist does not have to wait for the subject to reach the criterion accuracy before moving to the next level of treatment. Instead the treatment for the target sound patterns takes place in cycles. For example, if a child shows phonological processes such as "final consonant deletion" and "fronting", then the therapist can treat one of the phonological processes first for a short amount of time followed by treating the other process without waiting for the child to achieve mastery over the first process. The therapist can always bring the child back to the treatment of previously-treated pattern (or "re-cycle") to maximize the benefits by exposing the child to a wide variety of patterns almost simultaneously. Further, there is minimal pair training (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973), which mainly focuses on teaching the child to distinguish between the correct (target) and incorrect production of speech sounds. Beginning with the most stimulable sounds, this type of therapy approach can include using sounds in isolation or embedded in meaningful or non-meaningful contexts. For example, if there is a child who does not have a voicing contrast and mis-produces the sound /f/ as [v], then the minimal pair training might include exposing them to items such as *fan-van, fine-vine,* etc. A key goal of this approach is to reduce the homonymy resulting from the speech errors such that the children learn to produce two distinct sounds to signal two different meanings. From around two decades, evidence from the work of Rvachew and coworkers (Rvachew, 1994, 2005; Rvachew & Bernhardt, 2010; Rvachew & Nowak, 2001; Rvachew et al., 1999) reveal that use of perceptual training along with other traditional therapy techniques leads to enhanced therapeutic outcomes. Rvachew and colleagues, in line with the dynamic systems theory, propose the use of the most stimulable sounds first and to build the difficult concepts upon them rather than exposing the children to complex speech sounds directly, a notion supported by the complexity theories. Rvachew (1994) suggests using Speech Assessment and Interactive Learning System (Avaaz Innovations, 1995) as the perceptual training program. Rvachew (1994) investigated the effect of SAILS on 27 children, aged 42 to 66 months, with moderate to severe articulation difficulty in production of [ʃ]. The therapy with SAILS involves playing tapes containing the target sounds. Following the therapy sessions containing playing a variety of naturally produced exemplars of [ʃ], there was a significant improvement of perception and production of [ʃ] in these children. Rvachew suggests that this improvement following auditory perceptual training could be due to improvement in the internal representation of /ʃ/ in their subjects that allowed them to monitor their production accuracy and self-correct their errors. Further, Rvachew et al. (1999) found that with inclusion of SAILS in their treatment of speech sound disorders, the production accuracy went high up to 80% regardless of the pre-treatment baseline levels and stimulability. In order to test the efficacy of SAILS, Rvachew et al. (2004) conducted a study using SAILS (16 once-weekly sessions) on 34 children with moderate to severe speech production difficulties. The experimental group received the SAILS intervention for targeting different phonemes each week, in word-initial position for the first eight weeks and in word-final position for the last eight weeks of intervention. On the other hand, the control group did not undergo the SAILS training but listened to computerized books and answered to questions about pictures. After the training, both the groups were evaluated on the standardized tests for articulation. It was found that experimental group showed a significant improvement as compared to the control on the target items. Follow-up evaluation after a year showed that around 50% of subjects from the experimental group achieved normalized speech as compared to only 19% of subjects from the control group that achieved normalized speech. Overall, the intervention with SAILS has been found to significantly enhance the perception and production of the target items, although the total dosage of SAILS may vary depending on the severity of the disorder and other individual characteristics, from 30 minutes (Rvachew et al., 1999) to 60 minutes (Rvachew, 1994) to 160 minutes (Rvachew et al., 2004).

While there is evidence supporting the traditional-clinical approach to treatment, there are studies that support the treatment based on complex stimuli (Barlow & Gierut, 1999; Dinnsen & Elbert, 1984; Gierut, 2007; Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994). However, there are relatively few empirical treatment studies (Dinnsen, 2008; Dinnsen & Elbert, 1984; Gierut, 1989; Powell & Elbert, 1984) that have focused on examining the effects of complexity due to phonological properties (such as defined by markedness hierarchy).

In one of the first such study, Dinnsen and Elbert (1984) tested whether or not training with complex (more marked) stimuli induced generalization to simple (less marked) stimuli along with improvement on complex stimuli. They provided therapy to four children who depicted errors on fricatives and stops in their phonological profiles. As fricatives and stops are in an implicational relationship with fricatives being more marked than stops, two children were treated with fricatives while the other two were treated with stops. They found that the children who were treated with fricatives improved on fricatives and generalized to untreated stops while those who were treated with stops only improved on stops but did not generalize to untreated fricatives. Similarly, Powell and Elbert (1984) treated six children with speech sound disorders and found that those children who were treated with fricative-liquid clusters (more marked) not only showed treatment-induced effect in fricative-liquid cluster but also generalization effect on stop-liquid cluster while those who were trained with stop-liquid clusters just showed improvement in stop-liquid clusters but did not generalize to fricative-liquid ones. Recently, Dinnsen (2008) summarized findings from four studies where half of the children were treated with marked stimuli and the other half were treated with relatively unmarked stimuli. The stimuli used in these studies were onset clusters (more marked) and affricates (less marked) where these stimuli are in an implicational relationship with the onset clusters implying the affricates. It was found that with the treatment using clusters, there was an improvement in clusters and generalization to affricates while treatment with affricates only led to improvement in affricates but did not generalize to untreated onset clusters. Generalization is known to be indicative of widespread changes in the phonological system. The treatment-induced generalization in children, both within- and across-class categories, could be a reflection of their internal reorganization of conceptualizations of phonological categories (Gierut, 1989).

So, there is evidence favoring complex (Dinnsen & Elbert, 1984; Powell & Elbert, 1984; Dinnsen, 2008; Gierut, 1989) as well as traditional-clinical (Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Ferrier & Davis, 1973; Van Riper & Emerick, 1984; Winitz, 1969, 1975) procedures. However, there is a great variability in the magnitude of effects, study designs employed, sound stimuli used, and number of sessions involved, that makes it difficult to understand which approach is more efficacious than the other. Further, there are very few reports that have compared the two lines of treatment (e.g., Dinnsen & Elbert, 1984; Powell & Elbert, 1984; Dinnsen, 2008).

Furthermore, most of these case-reports originate from the treatment of English-speaking children. Phonological complexity that depends on markedness hierarchy or constraint ranking is usually dependent on the type and number of sounds in the repertoire of a language.

For example, languages with complex speech sounds such as clusters (bisyllabic or trisyllabic) are considered to have a more complex syllable structure than the languages with no clusters. In languages with elaborated syllable structure (such as English), because of the presence of sounds of variable complexity, one can get more elements (or types of sounds) arranged in an implicational hierarchy as compared to languages with relatively simpler syllable structure (such as Cantonese). As a result, in languages such as Cantonese that have smaller syllable inventories, we might see smaller markedness differences between the elements. Although there are case reports on comparing the effectiveness of the complex and simple therapy in English, comparing complex and simple therapy in a language with a relatively simple syllable structure (such as Cantonese) can further shed light on the efficacy of these therapy-types and will further contribute towards broadening the existing empirical base.

In the current study, we provided speech sound therapy to five Cantonese-speaking children for consonants in the initial position. The treatment was provided using single-subject designs (SSD) due to their benefits in treatment studies. Children with speech sound disorders most often differ from one another in their phonological profiles, quantitatively and/or qualitatively. If the data from these children with speech sound disorders are combined, they form a heterogeneous sample that cannot be used in group-level studies for evaluating the efficacy of treatment. On the other hand, SSD could prove useful with heterogeneous sampling because the data in SSD are collected from several time points including baseline, treatment and post-treatment such that each subject can serve as his/her own control. In addition, SSD is clinically more relevant in speech language pathology as it examines within-subject changes and the data obtained is specific to each subject. Furthermore, if needed, data from many subjects with SSD can be combined to view as a group.

5.2 Method

5.2.1 Participants

In this study, five subjects (2 females) aged 4 to 9 years who scored 1.5 SD below the mean on the Hong Kong Cantonese Articulation Test (HKCAT; Cheung et al., 2006), were recruited. All the subjects were children from Cantonese-speaking homes in Hong Kong (see Table 10 for details). These children were referred from articulation screening and teachers' reports from the nearby kindergarten and primary schools. All subjects had passed an oral mechanism examination to ascertain that they had no anatomical and obvious physiological defects causing articulation problems. They were reported to have no hearing difficulties and neurological defects, and all children passed the IQ evaluation. Primarily, these children had difficulties in production of two or more manners of consonants in the initial position. Out of the five subjects, two subjects (S1-2) were provided with simple therapy i.e. treatment with simple or unmarked treatment targets while the other three subjects (S3-5) were provided with complexity therapy i.e. treatment with complex targets.

Table 10. Demographic details and articulation characteristics of the subjects

Subject	**Age (y;m)**	**Gender**	**Phonological Processes**	**Major Sound errors**	**Treatment**
S1	8;5	F	De-affrication, Stopping	/ts/→[t], /tsʰ/→[s], /s/→[t], /s/→[ts], /s/→[ɵ], /s/→[s] (lisp)	Simple (i.e., for correct production of [s])
S2	4;8	M	Fronting	/kʷ/→[tʷ], /kʰ/→[tʰ], /k/→[t]	Simple (i.e., for

					correct production of [k])
S3	4;9	F	De-affrication, Stopping	/tsʰ/→[tʰ], /tsʰ/→[t], /ts/→[t], /s/→[t]	Complex (i.e., for correct production of [ts])
S4	4;7	M	De-affrication, Stopping	/tsʰ/→[tʰ], /ts/→[t], /s/→[t], /s/→[ts]	Complex (i.e., for correct production of [ts])
S5	4;2	M	De-affrication, Stopping	/tsʰ/→[tʰ], /tsʰ/→[t], /ts/→[t], /s/→[t]	Complex (i.e., for correct production of [ts])

5.2.2 Stimuli and materials

For testing, all the participants were administered HKCAT that contains 42 color photographs to elicit 51 familiar words containing all the 19 initial consonants, six final consonants, 11 vowels, 11 diphthongs, and six tones that occur in Cantonese. As the therapy only focused on initials, along with HKCAT, the children were also tested upon a set of phonological probes that contain 681 picturable vocabulary appropriate phonological probes consisting of all consonants (in initial position), vowels, diphthongs, and tones of Cantonese (see Table 11). Pictures corresponding to the phonological probes were also developed.

Table 11. Distribution of 681 phonological probes across place and manner of articulation

Place/ Manner	**Bilabial**	**Labio-dental**	**Alveolar**	**Palatal**	**Velar**	**Labio-velar**	**Glottal**
Plosive	/p/ 55		/t/ 82		/k/ 79	/k^w/ 14	
Fricative		/f/ 31	/s/ 114				/h/ 37
Affricate			/ts/ 91				
Nasal	/m/ 42				/n/ 18		
Lateral Approximant							
Approximant				/j/ 52		/w/ 17	

While the overall procedure of therapy was maintained the same across the subjects, the treatment targets varied depending upon whether the subjects were being treated with complex or simple therapy. Most of the subjects (n = 4) mis-produced affricates as fricatives and/or stops, and fricatives as stops and displayed this constraint hierarchy: *AFFR>*Fricatives >*t, ident {manner}. Among the subjects with this profile, those treated with complex treatment were treated with affricates (more marked) while those treated with simple treatment were treated with fricatives (less marked). One of the subjects in the current study displayed a place change (fronting) for both clusters (more marked) and stops (less marked) and since this subject was being treated for place change with simple therapy, the treatment targets were stops. Additionally, lesson plans for therapy were tailor-designed to suit the individual articulation profiles of these children. Broadly, the therapy material consisted of phonological probes for imitation, minimal pairs for differentiation between the correct and incorrect pronunciation, and age-appropriate speech topics for eliciting spontaneous speech samples (see Appendix-C).

5.2.3 Procedure

5.2.3.1 Testing

Testing was administered at the beginning of the therapy (Pre), immediately at the end of therapy (Post-I) and at a week's interval (maintenance evaluation; Post-II) from the end of the therapy. Testing consisted of evaluation of subjects' articulation of HKCAT and phonological probes. All the subjects were tested individually in a quiet room in our lab. After establishing rapport, the stimulus book of HKCAT was administered. To elicit a response from the participants, a standard carrier question was asked by the tester showing the picture stimulus. The participants were expected to produce spontaneously but if they found it difficult to produce it spontaneously (especially very young children), they were given the word by the testers for imitation. An imitated response was treated the same way as a spontaneously produced response.

Followed by the HKCAT evaluation, the subjects were evaluated on phonological probes. The pictures appeared on a laptop screen and the subjects had to say the word for the picture. In case the subjects did not produce the words spontaneously, they were given the words by the tester for imitation.

5.2.3.2 Therapy

The therapy was focused only on correct production of initial consonants. The therapy paradigm was both criteria and duration-dependent process. In order to complete the whole therapy procedure, the subjects had to either reach the pre-defined criteria (> 80% or 90%) at each stage or attend the whole program of 15 therapy sessions. Each therapy session lasted for 50 mins and there were 3-4 sessions of therapy in a week. There were three stages in the therapy (See Figure 18 for a detailed scheme of the process):

a. ***Imitation (maximum 5 sessions):*** The therapist said some words and the child had to repeat the same. Immediate feedback and corrective models, if needed, were provided. In a session, maximum of 10 blocks with 10 words in each block were administered. Scores were noted for each session. It was further divided into sub-stages consisting of imitation in isolation, syllables and words. The subjects had to obtain 80% at each of these sub-stages to go to the next sub-stage. If the subjects scored 80% on the imitation of words or got 5 sessions of therapy, they were moved to the next level consisting of therapy with minimal pairs.
b. ***Minimal pairs (maximum 5 sessions):*** In this stage, the therapist played sound tracks of words in its correct as well as incorrect realizations (with segments for the child). With the minimal pairs, the subjects had to go through these two levels: (a) *Identification*: The subjects were presented with a picture followed by which they heard two words in succession. For example, if a child incorrectly produces a consonant (/k/) in place of a cluster (/kl/), then a picture of a clock appears followed by two sounds, "clock" and "cock". The child had to identify the correct sound and produce the same. Corrective feedback was provided; (b) *Discrimination*: Here no pictures were provided. The subject was presented two productions, one correct and

the other incorrect one. The subject had to say whether the two sounds were same or different. Feedback and corrective models were provided on trial-to-trial basis. The subjects were moved to next level as soon as they reach criterion of > 90% scores or a maximum of five sessions.

c. ***Spontaneous speech (5 sessions):*** In each of the 5 sessions of therapy with spontaneous speech, the children were given a few topics from daily life to discuss. For example, “What’s your daily routine?”, “Who is your favorite superhero and why?” (See Appendix-C for an exhaustive list on the topics). The children were encouraged to speak spontaneously. During their spontaneous speech, errors in the targeted phonological structure were identified and corrective feedback was provided. The therapy in this stage continued until the subjects achieved 90% mastery on the affected sound or received five sessions.

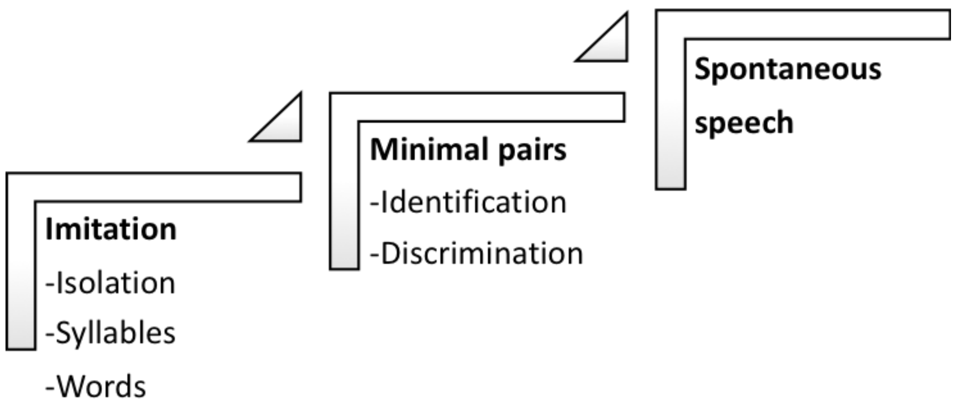

Figure 18. The course of therapy across its three stages, lasting for a maximum of 15 sessions. Criteria for passing each stage: (A) Imitation (Criteria: 80% or maximum five sessions); (B) Minimal Pairs (Criteria: 90% or maximum five sessions); (C) Spontaneous speech (Criteria: 90% or maximum five sessions).

5.2.3.3 Recording and Scoring

Children's productions were recorded using a lapel microphone attached to the children's clothing and stored in minidisc recorders (Sony Mz-B100 or Sharp MD-MT290H(S)). After collecting the speech recordings, two experienced listeners transcribed and scored their speech samples.

5.3 Results

5.3.1 Transcription reliability

The speech transcription data were evaluated for both intra- and inter-rater reliability by two expert independent raters in listening to audio files. The item-by-item agreement for inter-rater and intra-rater reliability were 89.4% and 93.6%, respectively. In case of a disagreement, opinion of a third rater was sought.

5.3.2 Therapy

As the therapy progressed, subjects' performance was tracked session by session. Figure 19 shows the subjects' progress on therapy across different stages (and sub-stages) and across sessions. It was found that all subjects used all the 15 sessions of therapy. Overall, it was found that the subjects who attended simple therapy learned at a much faster rate in the first two stages i.e. imitation (Figure 19(A)) and minimal pairs (Figure 19(B)) as compared to the subjects treated with complexity therapy. However, for the spontaneous speech, the subjects (S3-5) treated with complexity therapy showed more improvement (Figure 19(C)).

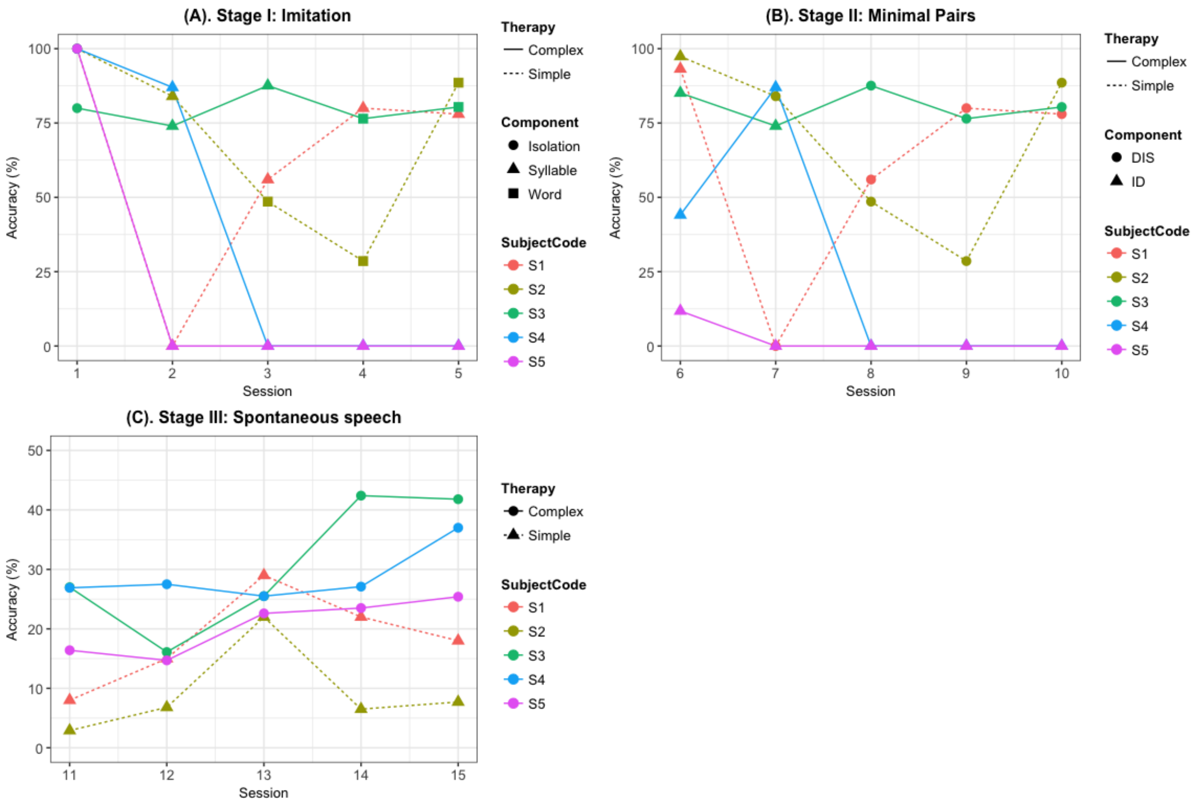

Figure 19. Subjects' progress on the therapy across the stages and sessions. Subjects S1 and S2 (treated with simple therapy) learned faster in the imitation ((A) Stage I) and minimal pairs ((B) Stage II) while the subjects S3, S4, and S5 (treated with complexity therapy) showed more improvement in the spontaneous speech stage ((C) Stage III). Abbreviations: ID = Identification; DIS = Discrimination.

5.3.3 Testing

5.3.3.1 HKCAT: Among the subjects treated with complexity therapy (S3-5), S3 and S5 showed a change in the overall raw scores of the initials from Pre- to Post-II while S4 showed a decline from Pre- to Post-II. In comparison, the subjects treated with simple therapy (S1-2) slightly improved on the overall HKCAT score from Pre- to Post-II. As HKCAT contains all speech sounds in all combinations, the improvements following the therapy look minuscule (Figure 20). In order to fully understand the effects of therapy on the outcome variables, we evaluated the subjects' production of phonological probes.

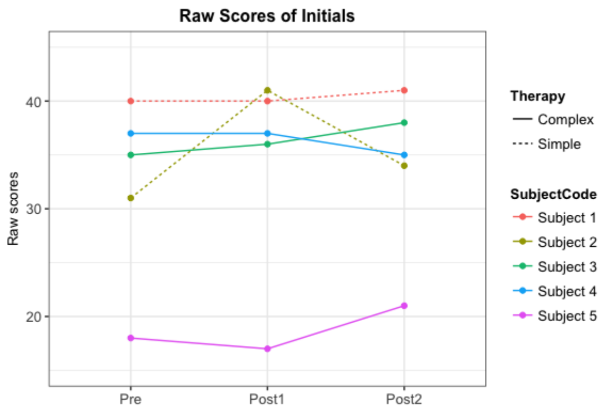

Figure 20. Comparison of subjects' trajectory across the evaluations. Pre: evaluation before the first session of the therapy; Post-I: evaluation after the last session of the therapy; Post-II: evaluation after a week from Post-I.

5.3.3.2 Phonological probes

5.3.3.2.1 Simple therapy

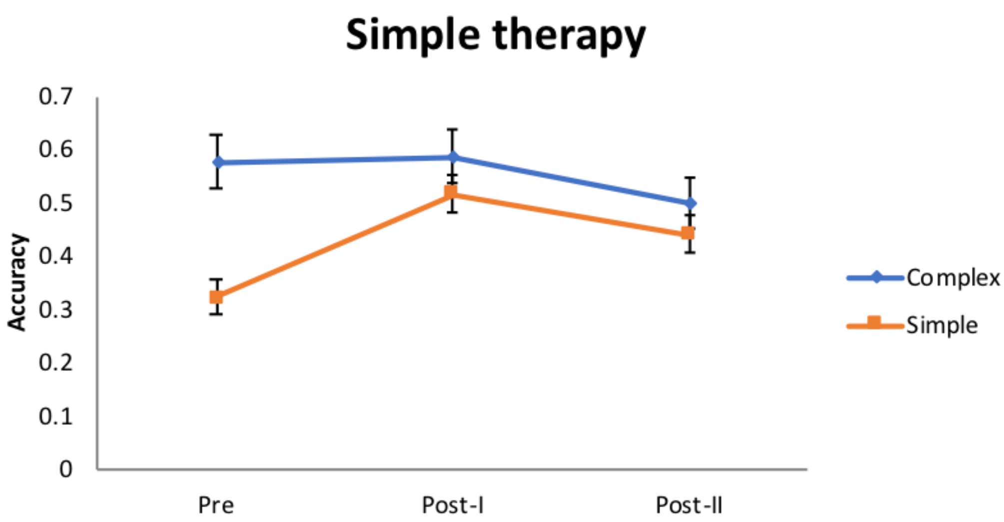

Figure 21. Comparison of average accuracy of speech sound production of complex and simple sounds following simple therapy.

We combined the production accuracy data of S1 and S2 across the three evaluations for both complex and simple speech sounds. We found that training subjects with simple or unmarked speech sounds led to an improvement of accuracy scores for the simple speech sounds (from Pre-therapy to Post-I) but not complex speech sounds (Figure 21).

Before the therapy, S1 displayed an articulatory profile with problems in production of affricates and fricatives. Affricates were realized as fricatives (/ts^h/→[s]) and stops (/ts/→[t]) while fricatives were realized as affricates (/s/→[ts]), stops (/s/→[t]), and lisped-fricatives (/s/→[s(lisp) s̪]) (Figure 22). After the simple therapy that used fricatives as the treatment targets, we saw an improvement in production of fricatives that were being realized as stops, along with reduced lisping. However, we did not find any improvement in the correct production of affricates.

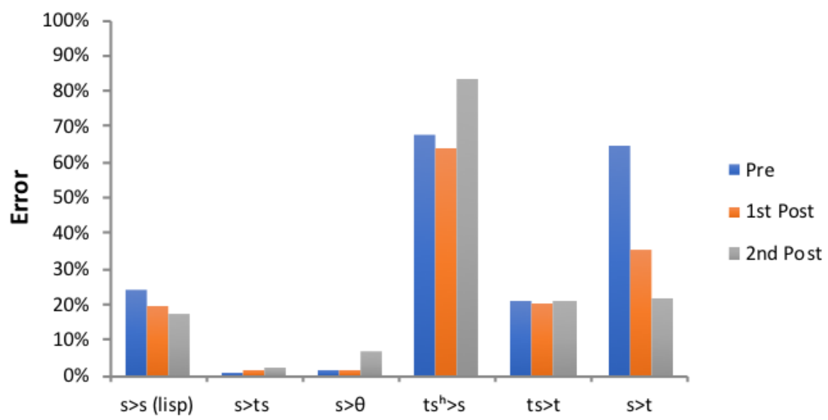

Figure 22. Articulatory profile of S1 across the three evaluations

S2 displayed a profile with *fronting* with major errors in stops. More specifically, the subject misarticulated /k^w/ as [t^w] and /k/ as [t] (Figure 23). We provided therapy to this subject for

/k/-/t/ distinction. We found that the subject improved on the correct production of [k] but did not improve on the production of [k^w] sound.

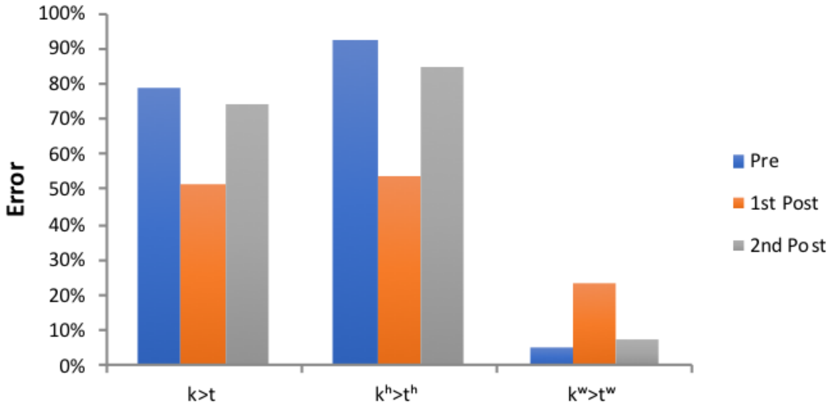

Figure 23. Articulatory profile of S2 across the three evaluations

In sum, it was found that treating with simple stimuli led to improvement on the simple speech sounds but not complex speech sounds.

5.3.3.2.2 Complexity therapy

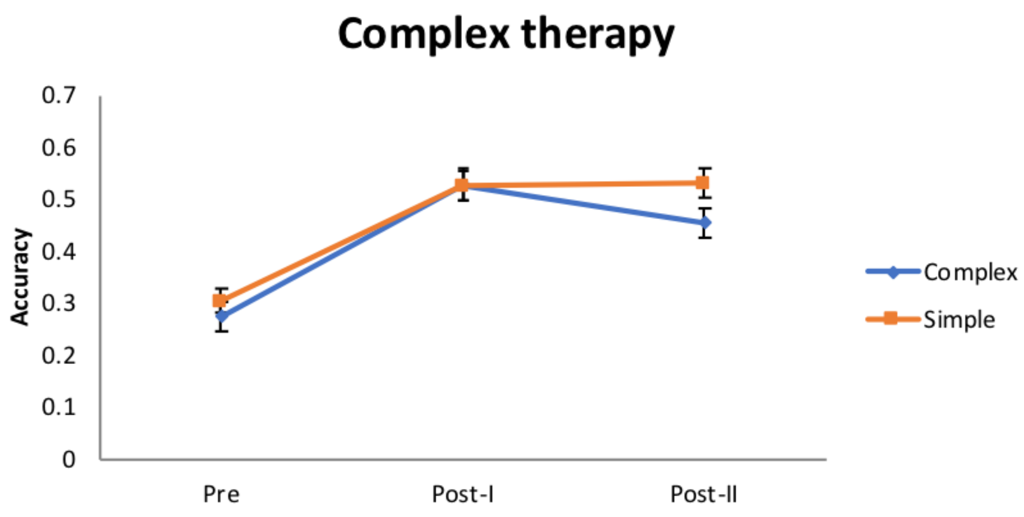

Figure 24. Comparison of average accuracy of speech sound production of complex and simple sounds following complexity therapy.

We combined the production accuracy data of S3, S4, and S5 across the three evaluations across both complex and simple speech sounds. Comparing the data from Pre-therapy (Pre), Post-therapy (Post-I) and Maintenance phase (Post-II), we found that the production accuracy for both complex and simple sounds improved following training with complex or marked sounds (Figure 24).

Basically, the S3-5 misarticulated affricates as fricatives (S3) or stops (S4-5), and fricatives as stops (S3-5). After the therapy, generally, it was found that the error rates were reduced for affricates and fricatives. Along with post-therapy, we found that there was maintenance of the outcomes of therapy for S3 and S4, but not for S5. The improvement was most robust for S3 and least robust for S5.

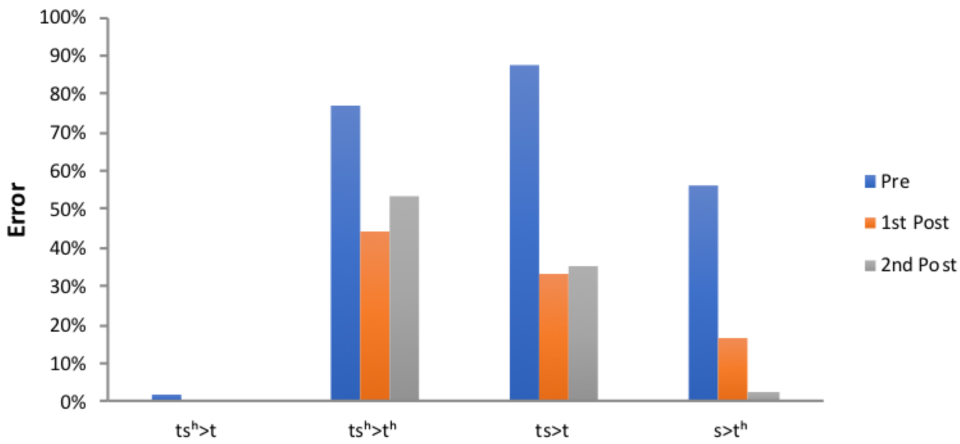

Figure 25. Articulatory profile of S3 across the three evaluations

S3 showed a decrease in error rate for affricates (/ts^h/→[t], /ts/→[t], /ts^h/→[t^h]) and fricatives (/s/→[t^h]) across the post-therapy (Post-1) and maintenance phase evaluation (Post-2) (Figure 25). S4 showed a decrease in error rate for aspirated affricates (/ts^h/→[t]) while the unaspirated affricates (/ts/→[t]) were resistant to therapy. Additionally, there was a decrease in error rate for fricatives that were being produced as stops (/s/→[t]) before the therapy. But, there was no change in error rate for fricatives being produced as affricates (/s/→[ts]) (Figure 26).

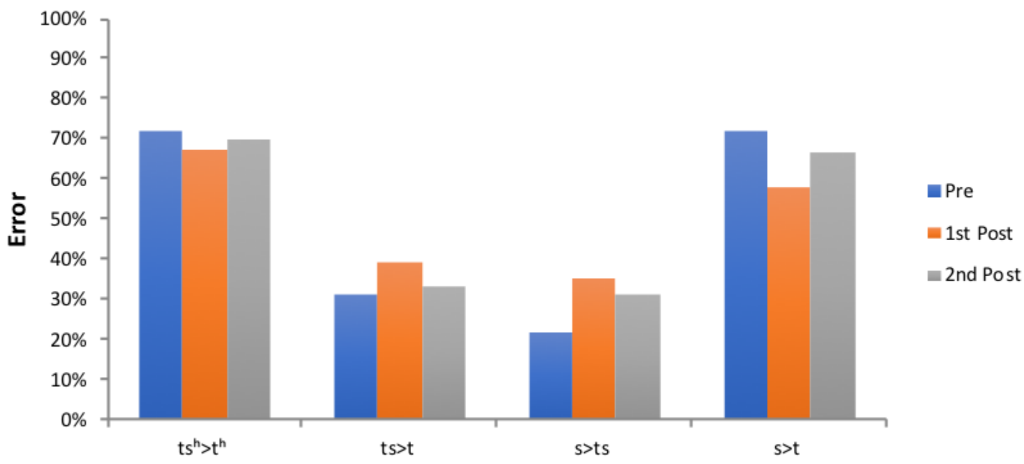

Figure 26. Articulatory profile of S4 across the three evaluations

Similarly, S5 showed a decrease in error rate of aspirated affricates and not unaspirated affricates (Figure 27). Additionally, there was a decrease in error rate of fricatives (/s/→[t]).

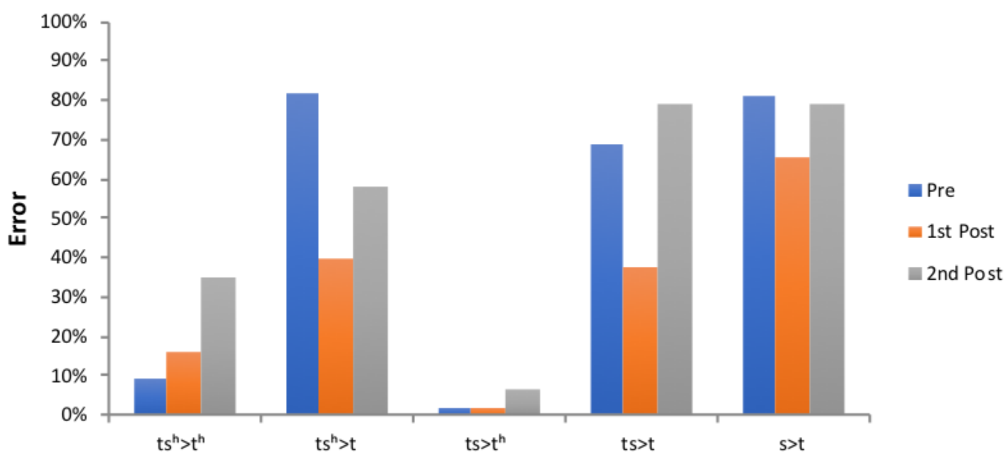

Figure 27. Articulatory profile of S5 across the three evaluations

In sum, it was found that treatment with complex speech sounds led to improvement on both complex and simple speech sounds.

5.4 Discussion

In the current study, we aimed at investigating whether complex input or simple input is more important in driving speech sound development. We examined this by comparing the performance of subjects treated with simple therapy to those treated with complexity therapy. Overall, we found that though the subjects treated with simple therapy learned at a faster rate in the first two stages of therapy (imitation and minimal pairs) as compared to those who were treated with complexity therapy, these subjects could not maintain their rate in the last stage (Stage III) of treatment with spontaneous speech. Instead, we noted that the subjects who were treated with complex stimuli tended towards performing better in the spontaneous speech stage. Further, in the post-therapy (Post-I) and maintenance evaluation (Post-II), we noted that the subjects treated with complex stimuli showed enhanced articulation scores for both complex and simple speech sounds while those who were treated with simple stimuli showed improvement only on articulation of simple speech sounds but not complex stimuli. For example, when the subjects who mis-produced affricates as fricatives, and fricatives as stops, were treated with affricates that rank higher in markedness hierarchy as compared to fricatives and stops (*AFFR>*Fricatives >>*t, ident {manner}), there was a modification or re-ranking of the markedness hierarchy (ident {manner}>>*AFFR,*Fricatives ,*t) so that both affricates and fricatives are produced correctly.

The findings from the current study are consistent with the previous findings of Gierut and coworkers (Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) on the use of complex speech input in maximizing improvement in correct production of speech sounds in children with speech sound disorders. These findings are in a general agreement with the language learnability models, outlined within the context of universal grammar (Wexler, 1982; Wexler & Culicover, 1980). From the current findings, it seems that complex input is more efficacious in driving development of both complex and simple sounds while simple input may just promote the development of simple speech sounds without inducing generalization to production of complex speech sounds. Further, the current findings can also be explained by constraint demotion or differential promotion of constraints in the implicational hierarchical arrangement, following the exposure to complex input. This constraint rearrangement or re-ranking facilitates speech sound development. For example, in Lleó & Prinz's study (1996), when the subjects with articulation difficulties on affricates and clusters were treated with clusters (more marked), it led to demotion of markedness constraints of both clusters and affricates and promotion of faithfulness constraints in the markedness hierarchy leading to development of both marked and unmarked sounds. On the other hand, when the subjects were treated with affricates (less marked), it just led to demotion of its markedness constraint beyond the faithfulness constraint. However, the cluster productions remained unchanged because its markedness constraint couldn't undergo demotion below the faithfulness constraint. In sum, when a complex input is used, it maps on to innate linguistic mechanisms to unlock and promote the development of both complex and simple structures while if a simple stimulus is used, it does not lead to unlocking of other untreated complex structures.

The findings from the current study have potential implications towards clinical practice. Phonological disorders, one of the most prevalent child language disorders, constitute a major portion of caseload for practicing pediatric speech language pathologists (SLP) (Johnson, 2004; Thomas, 2002). The prevalence of phonological disorder in the United States ranges from 3 to 13%. Further, speech sound disorder affects 10% of pre-school and school-aged children constituting to about 99% of caseloads of the SLPs practicing at schools (National Institute of Deafness and Other Communication Disorders, 1994). Phonological disorders could have a profound impact on children's academic skills including spelling, reading, and mathematics (Bird et al., 1995; Catts, 1993; Catts & Kamhi, 1986; Clarke-Klein & Hodson, 1995; Hoffman, 1990; Hoffman & Norris, 1989; King et al., 1982; Lewis & Freebairn, 1992; Shriberg & Kwiatkowski, 1985; Webster & Plante, 1992). Children with phonological disorders usually do not obtain similar educational and employment level as their typically developing peers (Thompson et al., 2003; Thompson et al., 1998). Given the heavy caseload on the practicing pediatric SLPs, high prevalence and far-reaching effects of childhood phonological disorder later in the adult life, use of a more efficient intervention technique is warranted. With the use of complex training technique, one can get far more benefits in a shorter span of time. Besides the studies in speech sound disorders, studies in treatment of syntactic deficits in aphasia (Thompson et al., 2003; Thompson et al., 1998) report efficiency of treatment based on complex stimuli. For example, Thompson et al. (1998) reported that the subjects treated with complex syntactic structures reached the criterion accuracy in 13 sessions as compared to 34 sessions needed by the subjects treated with simple structures. Similarly, Thompson et al. (2003) reported that their subjects treated with complex structures required only 12 sessions as opposed to 28 sessions required by the subjects treated with simple structures.

5.5 Future directions

The current findings are based on defining complexity from a perspective of implicational markedness. In the future, studies could be conducted to test the effect of other types of stimuli-dependent factors on complexity of speech sounds. For example, frequency of occurrence, homophony, and phonological neighborhood could be some of these factors. Further, findings of the current study are based on treatment of children with speech sound disorders using single subject designs. However, in order to gain more confidence in the findings, future studies should be conducted using randomized controlled designs that are considered the highest level of evidence by ASHA (Robey, 2004) and the ("Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009)," 2009).

Chapter 6

Conclusion

6.1 Summary and conclusion

Speech sound acquisition is essential to spoken language. The mechanisms underlying speech sound acquisition are a topic of ongoing debate. One of the intriguing research questions is whether speech sound acquisition is driven by exposure to simple speech sounds that are unmarked, easy, and are acquired early or by exposure to complex sounds that are marked, hard, and acquired later. The focus of the current dissertation has been to resolve this longstanding debate by contributing answers via four different approaches: (1) ***Meta-analysis***, where data from the relevant treatment-based literature were extracted, processed, and combined to understand whether it is complex input or simple input that leads to maximum improvement in speech sound production in children with speech sound disorders; (2) ***MaxEnt modeling***, where the trajectory of the acquisition of speech sounds in typically developing children and those with speech sound disorders were compared using a maximum entropy modeling technique, to understand the importance of complex and simple input; (3) ***Artificial language training***, where Cantonese-speaking adults trained with complex speech stimuli were compared with those that were trained with simple speech stimuli in a pseudo word-picture association task; and (4) ***Speech therapy***, where children with speech sound disorders from Cantonese-speaking homes treated with complex speech sounds were compared with those who were treated with simple speech sounds.

The above four approaches to address the research question stem from a combination of analytical literature review, experimental investigation, and linguistic analyses. Conducting a systematic analytical review via meta-analysis has been considered as an important avenue for consolidating and synthesizing research evidence (Collins & Fauser, 2005). Meta-analysis can provide a quantitative view of the findings from the literature by comparing and combining the effect sizes from various studies which are otherwise not viable to interpret due to smaller sample sizes, and variability in the magnitude of effects in the available studies. However, meta-analysis could be affected by the quality of studies that are available and thus needs to be supplemented by experimental investigation conducted on subjects with and without disorders. Conducting treatment-based research has been considered as an excellent method to determine the effect of stimuli as it allows selective manipulation of treatment variables to observe the effects on the atypical population (Gierut, 2001). However, when conducting treatment-based research in a population with disorders, it is not always possible to maintain the homogeneity between the subjects that could stem from variation in the severity of their disorder, and/or from their type of errors. In order to avoid these problems of heterogeneity and small sample sizes, it is necessary to supplement research with a training-based experimental investigation on adults. Given that children exhibit better plasticity for training as compared to adults, if the training-induced changes are apparent in adults, it is expected that these changes would be generalizable to children. In speech-training studies, changes in the electrophysiological measures have been considered as an index of improvement following training. Training-induced changes have been found to be apparent electrophysiologically first, followed by changes in behavior (Tremblay et al., 1998). It is known that speech and language experience leads to changes in pre-attentive neural processing (Chandrasekaran et al., 2007; Cheour et al., 2000; Näätänen et al., 2007; Tremblay et al., 1997, 1998). Thus, by conducting an electrophysiological investigation in conjunction with behavioral measurements, one can ascertain that the changes in behavior are indeed a result of training. In addition to addressing the research question experimentally, there is a need to conduct linguistic analyses that consider the phonological system as a whole. Conducting an in-depth linguistic analysis provides deeper insight regarding the development of all speech sounds in the phonological repertoire. Examining the research question with a combination of techniques from different standpoints, the current dissertation aims at providing a converging and conclusive answer to whether it is the exposure to complex speech sounds or simple speech sounds that is required to facilitate speech sound development.

The role of simple speech sounds in driving speech sound acquisition is supported by the traditional theories (for example, behaviorist theories, scaffolding theories, connectionist view, and dynamic systems theory) while the importance of complex speech sounds is supported by the linguistic-based complexity theories (for example, generative phonology, nonlinear phonology, natural phonology, and optimality theory). While there are both non-clinical (e.g., corpus-based, computational, diary study) and clinical (treatment-based) studies (Barlow & Gierut, 1999; Dinnsen & Elbert, 1984; Gierut et al., 1987, 1996; Morrisette et al., 2003; Powell et al., 1991; Tyler & Figurski, 1994) that reveal the importance of complexity in speech input, there are also studies (Behrens, 1998; Blache & Parsons, 1980; Blache et al., 1981; Elbert et al., 1980; Elman et al., 2006; Ferrier & Davis, 1973; Tomasello, 2003; Tomasello & Brooks, 1999; Van Riper & Emerick, 1984; Winitz, 1969, 1975) that support the usefulness of simple speech input for speech sound development. However, there is no clear consensus on whether it is complex input or simple input that is needed the most to drive speech sound acquisition. Though non-clinical studies provide valuable information about the role of complex and/or simple stimuli in acquisition, they do not allow a direct quantitative comparison of the effects of complex and simple input on speech sound development. In comparison, treatment-based studies provide an excellent vehicle to compare the effects of complex and simple stimuli by allowing selective manipulation of the treatment variables to evaluate the effects in the atypical population. In doing so, treatment-based studies also allow testing of the psychological reality of theories that support the use of complex and/or simple input for speech sound development. However, most of the previous treatment-based findings rely on case reports involving small subject samples from English-speaking homes, and do not analyze the phonological system as a whole. Further, in the previous studies, there is a lot of variability in the magnitude of effects, methodology used, and the number of training sessions involved that make it all the more difficult to understand which approach is more efficacious than the other. In order to settle this longstanding debate, the focus of the current dissertation has been to investigate this problem multi-dimensionally with four research studies that included conducting a meta-analysis on the existing literature, analyzing the trajectory of speech sound development in typically developing children and those with speech sound disorders, comparing the effect of training adults on complex vs. simple stimuli in an artificial language training paradigm, and comparing the effect of therapy using complex and simple stimuli on children with speech sound disorders from Cantonese-speaking homes. By looking at this research question multifacetedly, overcoming the limitations posed by the previous studies, I sought to provide a clearer and more comprehensive answer to whether it is complex input or simple input that more efficiently contributes to speech sound development.

In the meta-analysis study (Study 1; Chapter 2), using a list of inclusion criteria, 281 studies from the past three decades were narrowed down to 15 studies where children with speech sound disorders were treated with complex and/or simple speech sounds. After extracting, processing, and combining the effect sizes from these studies to produce forest plots, it was found that treatment with complex speech sounds not only improves the treated complex speech sounds but also generalizes to untreated simple speech sounds. In comparison, treatment with simple speech sounds only improved treated simple speech sounds while the improvement did not extend to untreated complex speech sounds. Conducting a meta-analysis provided a platform for combining and comparing the magnitude of effects from the previous research reports to bring out definitive findings on the comparison of the usefulness of complex vs. simple speech sounds in the treatment of speech sound disorders that could not be previously done due to the small sample sizes and variability in the magnitude of effects.

In the MaxEnt modeling study (Study 2; Chapter 3), phonological inventories of 61 3-6-year-old typically developing children and those with speech sound disorders were analyzed using Maximum Entropy grammar modeling. Based on the patterns of development of constraint weightings across the age groups (3-3; 11, 4-4; 11, 5-5; 11), it was found that within speech sound disorders, there were “delayed” and “deviant” sub-categories. Children in the “delayed” sub-category showed a similar trajectory of the development of complex and simple speech sounds as typically developing children while children in the “deviant” sub-category showed a trajectory of development different from the other two groups. Since one of the fundamental principles and a pre-requisite behind the use of complexity-based therapy is that typically developing children and those with speech sound disorders have a similar trajectory of development (Gierut, 2008), consistent with the findings of this study, we speculated on the types of treatment strategies needed for children with “delayed” and “deviant” phonological development. Conducting MaxEnt modeling on these data allowed analysis of the phonological system as a whole rather than analyzing individual sounds or sound patterns which was a limitation of the previous studies.

In the artificial language training study (Study 3; Chapter 4), Cantonese-speaking adults (N = 96) trained with complex stimuli were compared using behavioral and electrophysiological measures with those who were trained with simple stimuli in an artificial language training paradigm. It was found that the subjects who were trained with complex stimuli showed improvement with regard to complex stimuli and generalized to simple stimuli while the subjects trained with simple stimuli improved with regard to simple stimuli but did not generalize to untreated complex stimuli. These findings were visible at both behavioral and neurophysiological levels. From the training-induced generalization to untreated complex and simple speech sounds, neurophysiologically, it can be ascertained that complexity can promote changes in speech sound development in a rule-governed manner. Further, these findings revealed the neurophysiological reality of markedness hierarchy in necessitating acquisition of speech sounds. With a large subject sample of adults, random allocation of subjects into groups, homogeneity, self-replication, experimental control, and use of both behavioral and electrophysiological measures, this study provides a comprehensive contribution to the usefulness of complex vs. simple stimuli in facilitating speech sound development.

In the speech therapy study (Study 4; Chapter 5), five children diagnosed with speech sound disorders were included. Three children were treated with complexity therapy while the other two children were treated with simple therapy. Overall, it was found that the complexity therapy led to improvement with regard to treated complex and untreated simple speech sounds while simple treatment led to improvement with regard to treated simple speech sounds but did not improve the production of untreated complex speech sounds. This study, being one of the first studies conducted in children from non-English-speaking homes, broadens the existing empirical base on the use of complexity therapy in children with speech sound disorders.

The findings from these four studies corroborate that exposure to complexity in speech sound structure plays a vital role in speech sound development by inducing widespread generalization in the phonological system. Specifically, exposure to complex input leads to the development of both complex and simple sounds in a rule-governed manner while exposure to simple stimuli only leads to the development of simple stimuli but does not promote the development of complex stimuli. This overall finding is consistent with the models of language learnability in the context of universal grammar (Wexler, 1982; Wexler & Culicover, 1980). The current findings, more specifically, can be explained by constraint demotion or differential promotion of optimality theory constraints according to which, when a complex or marked speech sound is introduced as an input, it leads to unlocking structures of similar or lesser markedness. While the overall findings from the current dissertation support the importance of complex input in promoting speech sound development, the current findings also shed light on the potential efficacy of complex vs. simple input depending on the trajectory of speech sound development in children with speech sound disorders. In Study 2 (Chapter 3), it was found that the children with speech sound disorders could be classified as "delayed" and "deviant" based on their trajectory of development as compared to typically developing children. Gierut (2008) proposed that complex input could be more beneficial in promoting speech sound development in children with delayed trajectories. In light of this proposal and with the current data from 3-6-year-old children, we speculate that children with deviant trajectories might benefit from exposure to simple input first while children with delayed trajectories will benefit from exposure to complex input first. However, given the limited number of age groups studied and cross-sectional nature of the data in this study, the speculations should be considered preliminary, and create scope for future studies to further investigate the effect of complex vs. simple input in children with delayed vs. deviant trajectories. Further, we know that the concept of complexity is not only limited to phonology. There are other types of complexity (Gierut, 2001) that might also affect speech sound development (see section 6.2 for more details).

6.2 Limitations and future directions

The four studies in this dissertation aimed to investigate the effects of complex vs. simple input on speech sound development while resolving the limitations of the previous studies, that included variability in magnitude of effects, sample sizes, and number of therapy sessions, research reports only from children from English-speaking homes, and disadvantages of single-subject designs. Though the studies reported in the current dissertation, collectively, overcome the limitations of the previous studies, there are some limitations to these studies.

Meta-analysis of the systematically reviewed literature, generally, is affected by the quality of studies that are included in it. In the current meta-analysis (Study 1), even though all the included studies were case reports with single-subject designs, there still existed heterogeneity among the included studies as the research designs of the included studies ranged from multiple to single baseline, AB and ABA types. Further, most of the studies lacked blinding that could result in increase in the Type-I error (detection of an effect when there is none). In addition, there was a considerable variability in the service delivery sites ranging from homes to clinics to schools. As a result, there is a possibility of dilution of effects due to these types of variability. As the currently available studies in this area have mostly used single-subject designs that are considered level 4 on the levels of evidence charted by the Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009), there is a need to conduct studies using randomized controlled designs that are considered as the highest level of evidence. This would ensure homogeneity among the studies to be included in a meta-analysis, and greater confidence in the obtained results.

Further, in order to understand the trajectory of the development of speech sounds in typically developing children and those with speech sound disorders, MaxEnt modeling (Study 2) was conducted on the phonological data from three age groups i.e. 3-3; 11, 4-4; 11, 5-5; 11-year-olds. Though these data provide a fair idea of the comparison of the trajectory of phonological development for typically developing children and those with speech sound disorders across the age groups, the data are cross-sectional in nature. Cross-sectional data could be affected by the individual variability across the age groups. In order to control for individual variability, future studies should be conducted using longitudinal measurements by following up the same set of subjects across the age intervals.

Further, the speech therapy study (Study 4) was conducted on five children with speech sound disorders using single-subject designs. Though this study on Cantonese-speaking children broadens the currently existing empirical base on the efficacy of complexity therapy and overcomes the limitation of the previous studies of being limited to children from English-speaking homes, this study has the shortcomings of having a small sample size and lack of multiple baselines in single-subject design. In addition, there was an individual variability in the extent and type of sounds that were misarticulated by these children. Although achieving total homogeneity across the phonological profiles of children with speech sound disorders is not always possible, future studies should consider using a bigger sample size and multiple-baseline designs. Having evaluations done at several time-points, as in a multiple-baseline design, ensures stability and provides an opportunity to combine the scores from various subjects, for further analyses.

In comparison, the artificial language training study (Study 3) was methodologically well-designed, especially in terms of randomization, experimental control, and self-replication. However, the extent to which the findings of this study are generalizable to the atypical population needs to be explored. Future studies could consider conducting this research on a homogeneous population of children with speech sound disorders. Population with disorders is often considered the best way to understand the psychological reality of theories (Gierut, 2001) of speech sound development.

Overall, though the studies in the current dissertation have limitations and create scope for future studies, combined with the findings of these studies, it can be concluded that complexity in speech sound structure plays a more important role in inducing more widespread changes in the phonological patterns as compared to exposure to simple speech sounds. While the current dissertation looked at the effects of linguistic/phonological complexity on speech sound development, the definition of complexity extends farther than linguistic markedness. Gierut (2001) proposed that the construct of complexity is multi-dimensional and in the context of speech sound development disorders, complexity can be viewed in terms of linguistic, psycholinguistic, articulatory-phonetic variables, and conventional clinical factors. Psycholinguistic complexity refers to the characteristics of words that influence the process of word recognition and production, for example, treatment with high-frequency words leading to greater generalization than treatment with low-frequency words (Gierut et al., 1999). Articulatory-phonetic complexity depends on the stimulability of words. For example, less stimulable sounds induce generalization to both stimulable and less stimulable sounds. Conventional clinical factors include factors such as consistency of errors, normative age of acquisition, and number of errors treated. For example, treating the subjects with two new sounds is more complex than treating the subjects with one new sound. While in the current dissertation I have examined the aspects related to linguistic/phonological complexity, future studies are needed to further expand this research using complexity due to psycholinguistic, articulatory-phonetic, and conventional clinical factors.

6.3 Implications

Taken together, the findings from the current dissertation suggest that exposure to complex input potentially plays a major contributor to speech sound development. These findings have implications for the field of education and rehabilitation. Traditionally, in the field of education, it is believed that when learning new concepts, one must begin with simpler concepts first, followed by learning more difficult concepts in an increasing gradation of difficulty. However, in light of the current findings, teachers/educators are encouraged to introduce difficult concepts first that would possibly generalize to the concepts of equivalent or lesser complexity, maximizing the benefits of learning in a shorter period of time. These findings have direct implications for treatment of speech sound disorders. Speech sound disorders affect around 10% of the pre-school and school-aged children in the United States, and it constitutes about 99% of caseloads of speech therapists providing their services in schools. Further, it is known that children affected by speech sound disorders at some stage of their lives, do not attain similar educational and employment levels as their typically developing peers. As there are lifelong effects of childhood speech sound disorders on the children's future personal and professional development, there is a need to provide the most efficient, time and cost-effective type of intervention. Using a complexity therapy, children with speech sound disorders can improve on the treated complex items as well as generalize to the untreated simple items in a shorter period of time.

Appendix-A

Table A.1. Confusion matrix of input and production of words' initial consonants by 3-year-old SSD children's (n=12). Rows denote the input while columns denote the output (or production). Highlighted ones are the violations to normative development.

	Output															
	3 yr old SSD	p	pH	t	tH	k	kH	f	?c	s	S	h	ts	tsH	kw	kHw
Input	pH	4	40	1	1			1				1				
	t			33		3										
	tH				23		4					2		4		
	k			10		49										
	kH			2	8	1	30			2		4				
	f	2	1					40				2		1		
	s	1		2		1				64			6	12		
	ts			7									29			
	tsH			1	2					5		1		35		
	kw	1		3		10									9	
	kHw			1		1	4	1								4

Table A.2. Confusion matrix of input and production of words' initial consonants by 4-year-old SSD children's (n=9). Rows denote the input while columns denote the output (or production). Highlighted ones are the violations to normative development.

	Output															
	4 yr old SSD	**p**	**pH**	**t**	**tH**	**k**	**kH**	**f**	**?c**	**s**	**S**	**h**	**ts**	**tsH**	**kw**	**kHw**
Input	**pH**	1	35													
	t			24		3										
	tH			1	23	1	2									
	k			18		27										
	kH	2			9		25									
	f	2	1					24								
	s			1	1					54			**2**			
	h															
	ts			2									25			
	tsH			1						2				33		
	kw			1		1									13	
	kHw	1													1	6

Table A.3. Confusion matrix of input and production of words' initial consonants by 5-year-old SSD children's (n=10). Rows denote the input while columns denote the output (or production). Highlighted ones are the violations to normative development.

	Output															
	5 yr old SSD	**p**	**pH**	**t**	**tH**	**k**	**kH**	**f**	**?c**	**s**	**S**	**h**	**ts**	**tsH**	**kw**	**kHw**
Input	**pH**	4	36													
	t			29		1										
	tH			3	34	1	2									
	k			5		45										
	kH	1			4	6	29									
	f	1						29								
	s				1	7				50	7			**3**		
	h															
	ts			2		4							24			
	tsH			2		4				4				30		
	kw					4		1							15	
	kHw							1								9

Appendix-B

Input table for MaxEnt Grammar Tool for 3-3;11-year-old typically developing children

Input	Output	Tokens	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
pH	p	0		1					1	1						1		
	pH	36		1					1	1					1			
	t	0			1		1			1						1		
	tH	0			1		1			1					1			
	k	0	1				1	1	1	1						1		
	kH	0	1				1	1	1	1					1			
	f	0					1				1	1		1		1		
	?c	0					1				1	1		1		1		
	s	0			1		1					1		1		1		
	S	0			1		1					1		1		1		
	h	0					1							1	1			
	ts	0			1		1						1	1		1		
	tsH	0			1		1						1	1	1			
	kw	0	2	1			1	1	1	1				1		1	1	
	kHw	0	2	1			1	1	1	1				1	1		1	
	m	0		1					1	1				1		1		
	n	0			1		1			1				1		1		
	N	0	1				1	1	1	1				1		1		
	l	0			1		1							1		1		
	j	0	1				1							1		1		
	w	0	1	1			1							1		1		
	?	0				1	1							1		1		1
t	p	0		1			1		1	1								

	pH	0		1			1		1	1					1	1		
	t	27			1					1								
	tH	0			1					1					1	1		
	k	0	1				1	1	1	1								
	kH	0	1				1	1	1	1					1	1		
	f	0					1				1	1		1				
	?c	0					1				1	1		1				
	s	0			1							1		1				
	S	0			1		1					1		1				
	h	0					1							1	1	1		
	ts	0			1								1	1				
	tsH	0			1								1	1	1	1		
	kw	0	2	1			2	1	1	1				1			1	
	kHw	0	2	1			2	1	1	1				1	1	1	1	
	m	0		1			1		1	1				1				
	n	0			1					1				1				
	N	0	1				1	1	1	1				1				
	l	0			1									1				
	j	0	1				1							1				
	w	0	1	1			1							1				
	?	0				1	1							1		1		1
tH	p	0		1			1		1	1						1		
	pH	0		1			1		1	1					1			
	t	0			1					1						1		
	tH	27			1					1					1			
	k	0	1				1	1	1	1						1		
	kH	0	1				1	1	1	1					1			

	f	0					1				1	1		1		1		
	?c	0					1				1	1		1		1		
	s	0			1							1		1		1		
	S	0			1		1					1		1		1		
	h	0					1							1	1			
	ts	0			1								1	1		1		
	tsH	0			1								1	1	1			
	kw	0	2	1			2	1	1	1				1		1	1	
	kHw	0	2	1			2	1	1	1				1	1		1	
	m	0		1			1		1	1				1		1		
	n	0			1					1				1		1		
	N	0	1				1	1	1	1				1		1		
	l	0			1									1		1		
	j	0	1				1							1		1		
	w	0	1	1			1							1		1		
	?	0				1	1							1		1		1
k	p	0		1			1		1	1								
	pH	0		1			1		1	1					1	1		
	t	1			1		1			1								
	tH	0			1		1			1					1	1		
	k	44	1					1	1	1								
	kH	0	1					1	1	1					1	1		
	f	0					1				1	1		1				
	?c	0					1				1	1		1				
	s	0			1		1					1		1				
	S	0			1		1					1		1				
	h	0					1							1	1	1		

	ts	0			1		1						1	1				
	tsH	0			1		1						1	1	1	1		
	kw	0	2	1			1	1	1	1				1			1	
	kHw	0	2	1			1	1	1	1				1	1	1	1	
	m	0		1			1		1	1				1				
	n	0			1		1			1				1				
	N	0	1					1	1	1				1				
	l	0			1		1							1				
	j	0	1				1							1				
	w	0	1	1			1							1				
	?	0				1	1							1		1		1
kH	p	0		1			1		1	1						1		
	pH	0		1			1		1	1					1			
	t	0			1		1			1						1		
	tH	2			1		1			1					1			
	k	1	1					1	1	1						1		
	kH	33	1					1	1	1					1			
	f	0					1				1	1		1		1		
	?c	0					1				1	1		1		1		
	s	0			1		1					1		1		1		
	S	0			1		1					1		1		1		
	h	0					1							1	1			
	ts	0			1		1						1	1		1		
	tsH	0			1		1						1	1	1			
	kw	0	2	1			1	1	1	1				1		1	1	
	kHw	0	2	1			1	1	1	1				1	1		1	
	m	0		1			1		1	1				1		1		

	n	0			1		1			1				1		1		
	N	0	1					1	1	1				1		1		
	l	0			1		1							1		1		
	j	0	1				1							1		1		
	w	0	1	1			1							1		1		
	?	0				1	1							1		1		1
f	p	0		1			1		1	1				1				
	pH	0		1			1		1	1				1	1	1		
	t	0			1		1			1				1				
	tH	0			1		1			1				1	1	1		
	k	0	1				1	1	1	1				1				
	kH	0	1				1	1	1	1				1	1	1		
	f	27									1	1						
	?c	0					1				1	1						
	s	0			1		1					1						
	S	0			1		1					1						
	h	0					1								1	1		
	ts	0			1		1						1	1				
	tsH	0			1		1						1	1	1	1		
	kw	0	2	1			1	1	1	1				1			1	
	kHw	0	2	1			1	1	1	1				1	1	1	1	
	m	0		1			1		1	1				1				
	n	0			1		1			1				1				
	N	0	1				1	1	1	1				1				
	l	0			1		1							1				
	j	0	1				1							1				
	w	0	1	1			1							1				

	?	0				1	1							1		1		1
s	p	0		1			1		1	1				1				
	pH	0		1			1		1	1				1	1	1		
	t	7			1					1				1				
	tH	0			1					1				1	1	1		
	k	0	1				1	1	1	1				1				
	kH	0	1				1	1	1	1				1	1	1		
	f	0					1				1	1						
	?c	0					1				1	1						
	s	63			1							1						
	S	0			1		1					1						
	h	0					1								1	1		
	ts	0			1								1	1				
	tsH	0			1								1	1	1	1		
	kw	0	2	1			2	1	1	1				1			1	
	kHw	0	2	1			2	1	1	1				1	1	1	1	
	m	0		1			1		1	1				1				
	n	0			1					1				1				
	N	0	1				1	1	1	1				1				
	l	0			1									1				
	j	0	1				1							1				
	w	0	1	1			1							1				
	?	0				1	1							1		1		1
ts	p	0		1			1		1	1				1				
	pH	0		1			1		1	1				1	1	1		
	t	5			1					1				1				
	tH	0			1					1				1	1	1		

	k	0	1				1	1	1	1				1				
	kH	0	1				1	1	1	1				1	1	1		
	f	0					1				1	1		1				
	?c	0					1				1	1		1				
	s	0			1							1		1				
	S	0			1		1					1		1				
	h	0					1							1	1	1		
	ts	22			1								1					
	tsH	0			1								1		1	1		
	kw	0	2	1			2	1	1	1				1			1	
	kHw	0	2	1			2	1	1	1				1	1	1	1	
	m	0		1			1		1	1				1				
	n	0			1					1				1				
	N	0	1				1	1	1	1				1				
	l	0			1									1				
	j	0	1				1							1				
	w	0	1	1			1							1				
	?	0				1	1							1		1		1
tsH	p	0		1			1		1	1				1		1		
	pH	0		1			1		1	1				1	1			
	t	4			1					1				1		1		
	tH	0			1					1				1	1			
	k	0	1				1	1	1	1				1		1		
	kH	0	1				1	1	1	1				1	1			
	f	0					1				1	1		1		1		
	?c	0					1				1	1		1		1		
	s	1			1							1		1		1		

	S	0			1		1					1		1		1		
	h	0					1							1	1			
	ts	0			1								1			1		
	tsH	31			1								1		1			
	kw	0	2	1			2	1	1	1				1		1	1	
	kHw	0	2	1			2	1	1	1				1	1		1	
	m	0		1			1		1	1				1		1		
	n	0			1					1				1		1		
	N	0	1				1	1	1	1				1		1		
	l	0			1									1		1		
	j	0	1				1							1		1		
	w	0	1	1			1							1		1		
	?	0				1	1							1		1		1
kw	p	0		1			1		1	1				1				1
	pH	0		1			1		1	1				1	1	1		1
	t	0			1		2			1				1				1
	tH	0			1		2			1				1	1	1		1
	k	7	1				1	1	1	1				1				1
	kH	0	1				1	1	1	1				1	1	1		1
	f	0					1				1	1		2				1
	?c	0					2				1	1		2				1
	s	0			1		2					1		2				1
	S	0			1		2					1		2				1
	h	0					2							2	1	1		1
	ts	0			1		2						1	2				1
	tsH	0			1		2						1	2	1	1		8
	kw	11	2	1				1	1	1							1	

	kHw	0	2	1				1	1	1					1	1	1	
	m	0		1			1		1	1				2				1
	n	0			1		2			1				2				1
	N	0	1				1	1	1	1				2				1
	l	0			1		1							2				1
	j	0	1				1							1				1
	w	0	1	1			1							1				1
	?	0				1	2							2		1		2
kHw	p	0		1			1		1	1				1		1		1
	pH	0		1			1		1	1				1	1			1
	t	0			1		2			1				1		1		1
	tH	0			1		2			1				1	1			1
	k	0	1				1	1	1	1				1		1		1
	kH	0	1				1	1	1	1				1	1			1
	f	0					1				1	1		2		1		1
	?c	0					2				1	1		2		1		1
	s	0			1		2					1		2		1		1
	S	0			1		2					1		2		1		1
	h	0					2							2	1			1
	ts	0			1		2						1	2		1		1
	tsH	0			1		2						1	2	1			1
	kw	0	2	1				1	1	1						1	1	
	kHw	9	2	1				1	1	1					1		1	
	m	0		1			1		1	1				2		1		1
	n	0			1		2			1				2		1		1
	N	0	1				1	1	1	1				2		1		1
	l	0			1		1							2		1		1

	j	0	1				1							1		1		1
	w	0	1	1			1							1		1		1
	?	0				1	2							2		1		2

Appendix-C

Topics for Spontaneous Speech Task

1. Daily routine
2. School life
3. Friends
4. Family
5. An interesting fable
6. Which subjects do you like most and least?
7. People you admire
8. Do you have pets? What animals do you like best?
9. Hobbies
10. Dream career
11. Dream house
12. Favorite TV program
13. Favorite cartoon character
14. Favorite food and drink
15. Travelling
16. What did you do today?
17. What did you do yesterday?
18. What are you going to do this weekend?
19. Leisure time
20. Extra-curricular activities
21. Favorite festival
22. Favorite game (board game, card game or group game)
23. Superhero (Who is your favorite superhero and why?)

24. Achievements

25. Favorite teacher

26. Favorite place in Hong Kong

27. What superpower would you like to have and why?

28. What present(s) would you like to receive for your next birthday?

29. What is your favorite season of the year?

30. What did you do for your mother in the last Mother's Day?

31. What did you do for your father in the last Father's Day?

32. What are your strengths?

33. Describe your perfect weekend.

34. If you could be anyone for a day, who would it be and why?

35. Talk about your class.

36. What would you do if your friends are sad?

37. What would you do if you had a thousand dollars?

38. Describe the most memorable dream you have had.

39. Describe the happiest moment in your life.

40. If you could have three wishes, what would they be?

41. Do you think studying is important? Why?

42. Where do you want to go with your mum?

43. Do you like Hong Kong and why?

44. If you could invent anything, what would it be?

45. If you could write a letter to anybody, who would you write to and why?

46. Favorite place

47. What would you do if you met an alien?

48. Do you remember your first day at school? How did it go?

49. If you were the school principal, what rules would you change?

50. Favorite sports

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