Musical training as a potential tool for improving speech perception in background noise

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Abstract

Understanding speech in background noise is a complex and challenging task that causes difficulty for many people, including young children and older adults. Musicians, on the other hand, appear to have an enhanced ability to perceive speech in noise. This has prompted suggestions that musical training could help people who struggle to communicate in complex auditory environments. The experiments presented in this thesis were designed to investigate if and how musical training could be used as an intervention for improving speech perception in noise.

The aim of Experiment 1 was to identify specific musical skills which could be targeted for training. Musical beat perception was found to be strongly correlated with speech perception in noise. It was hypothesised that musical beat perception might enhance speech perception in noise by facilitating temporal orienting of attention to important parts of the signal.

Experiments 2, 3 and 4 investigated this hypothesis using a rhythmic priming paradigm. Musical rhythm sequences were used to prime temporal expectations, with performance for on-beat targets predicted to be better than that for temporally displaced targets. Rhythmic priming benefits were observed for detection of pure-tone targets in noise and for identification of words in noise. For more complex rhythms, the priming effect was correlated with musical beat perception.

Experiment 5 used the metric structure within a sentence context to prime temporal expectations for a target word. There was a significant benefit of rhythmic priming for both children and adults, but the effect was smaller for children.

In Experiment 6, a musical beat training programme was devised and evaluated for a group of older adults. After four weeks of training, a small improvement in speech reception thresholds was observed. It was concluded that beat perception is a useful skill to target in a musical intervention for speech perception in noise.

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Table of Contents

List of Figures xi

List of Tables xiii

1 Introduction 1

1.1 Musical training and speech perception 1
1.1.1 Musicians as expert listeners 1
1.1.2 Evidence from musical training studies 2
1.1.3 Proposed mechanisms of transfer from music to speech 3
1.1.4 Musical training for speech perception in noise . . . 6
1.2 A brief introduction to auditory scene analysis 7
1.2.1 Setting the complex auditory scene 7
1.2.2 Auditory scene analysis 8
1.3 Selectively attending to target speech 9
1.3.1 Endogenous and exogenous cues 9
1.3.2 Attending to location 11
1.3.3 Attending to voice characteristics 13
1.3.4 Selective attention is limited by sensory processing . 14
1.4 Reconstructing a degraded or incomplete speech signal . . . 15
1.4.1 The role of linguistic knowledge 16
1.4.2 Listening to speech in modulated noise 17
1.5 The importance of temporal information in speech 18
1.5.1 Orienting attention in time 19
1.5.2 Rhythmic priming during speech listening 22
1.6 A lifespan perspective on speech perception in noise 23
1.6.1 Development during childhood 24
1.6.2 Decline during older adulthood 25
1.7 Musician advantage for speech perception in noise 27
1.7.1 Evidence from group comparison studies 27
1.7.2 Evidence from a longitudinal training study 32
1.8 Designing a musical training programme 33

1.8.1 Pitch and melody 35
1.8.2 Rhythm and beat 35
1.9 Research questions and outline of thesis 36

2 General methods 39
2.1 Quantifying musical experience 39
2.1.1 Measuring musical training 39
2.2 Assessing musical skills 41
2.2.1 Melody and rhythm 41
2.2.2 Musical beat perception 42
2.3 Testing speech-in-noise perception 43
2.3.1 Choosing a sentence test 45
2.3.2 Selecting noise maskers 47
2.4 Psychophysics 49
2.4.1 Adaptive staircases 50
2.4.2 Method of constant stimuli 51
2.4.3 Threshold estimates from fitted functions 51
2.4.4 Quantifying rhythmic priming effects 53

3 Investigating musical skills for speech perception in noise 55
3.1 Introduction 55
3.2 Experiment 1 56
3.2.1 Aims 56
3.2.2 Methods 59
3.2.3 Results 64
3.3 Discussion 70
3.3.1 Evaluation of noise maskers 70
3.3.2 Musical experience and speech-in-noise perception . . 71
3.3.3 Musical beat perception and speech-in-noise perception 71

4 Rhythmic priming of anticipatory attention to targets in noise 75
4.1 Introduction 75
4.2 Experiment 2: Priming with a simple beat 76
4.2.1 Aims 76
4.2.2 Task design 76
4.2.3 Methods 81
4.2.4 Results 85
4.2.5 Discussion 90
4.3 Experiment 3: Priming with musical rhythms 92
4.3.1 Aims 92
4.3.2 Task design 93
4.3.3 Methods 95
4.3.4 Results 100
4.3.5 Discussion 106
4.4 Experiment 4: Priming with speech sounds 109
4.4.1 Aims 109
4.4.2 Task design 109

4.4.3 Methods 110
4.4.4 Results 111
4.4.5 Discussion 113
4.5 Summary 114

5 Rhythmic priming of attention during speech listening 115
5.1 Introduction 115
5.2 Experiment 5 116
5.2.1 Aims 116
5.2.2 Task design 117
5.2.3 Methods 118
5.2.4 Results 122
5.3 Discussion 124

6 Training musical beat perception 127
6.1 Introduction 127
6.1.1 Training musical beat perception 128
6.2 Experiment 6 130
6.2.1 Aims 130
6.2.2 Methods 131
6.2.3 Results 135
6.3 Discussion 148

7 General discussion 151
7.1 Question 1: Are specific musical skills associated with speech perception in noise? 151
7.1.1 Why might musical beat training transfer to speech perception? 152
7.1.2 Consideration of other musical skills 154
7.1.3 Interpreting differences in speech reception thresholds 155
7.1.4 Beat perception in specific populations 156
7.2 Question 2: How might beat perception contribute to speech perception in noise? 158
7.2.1 Musical beat perception and rhythmic priming 158
7.2.2 Converging evidence from neuroscience 159
7.2.3 What is a meaningful difference in threshold? 161
7.2.4 Adaptations of the rhythmic priming paradigm . . . 162
7.3 Question 3: Can short-term beat training improve speech perception in noise? 164
7.3.1 Considerations for future training studies 164
7.4 Conclusion 167

References 169

List of Figures

1.1 Example configuration for a selective attention experiment . 12
1.2 Data from speech perception studies 14
1.3 Dynamic attending theory 20
1.4 Musician advantage for speech perception in noise 29
1.5 Lifespan development of speech perception in noise 33
1.6 Research questions 36

2.1 The Goldsmiths' Musical Sophistication Index 40
2.2 The Matrix Sentence Test 46
2.3 Waveforms of the three noise maskers 49
2.4 The psychometric function 50
2.5 Fitting psychometric functions 52
2.6 The quadratic coefficient as a measure of rhythmic priming 53

3.1 Mean speech reception thresholds with the three noise maskers 63
3.2 Scatter matrix of the relationships among predictor variables 65
3.3 Scatter matrix of relationships between predictor variables and speech perception in noise measures 67
3.4 Scatter plots of beat perception and speech-in-noise measures 69
3.5 Beat processing as a link between musical training and speech perception in noise 73

4.1 Waveforms of target words 77
4.2 Word list used in Experiment 2 82
4.3 Schematic diagram of a trial in the speech discrimination task 82
4.4 Schematic diagram of a trial in the tone detection task . . . 83
4.5 Schematic diagram showing the target positions with jittered intervals 83
4.6 Mean thresholds for the speech task in Experiment 2 86
4.7 Results of the tone detection task 88
4.8 Results of the tone detection task for all 6 target positions . 89
4.9 Rhythmic priming sequences 97

4.10 Word list used in Experiment 3 97
4.11 Schematic of a trial in Experiment 3 98
4.12 Subjective beat ratings of the priming sequences 101
4.13 Results of the speech discrimination task 102
4.14 Comparison of speech results from Experiments 2 and 3 . . 102
4.15 Results of the tone-detection task from Experiment 3 104
4.16 Comparison of tone task results from Experiments 2 and 3 . 105
4.17 Musical beat ability associates with rhythmic priming effect 106
4.18 Results of the speech discrimination task from Experiment 4 112
4.19 Results from six individual participants 113

5.1 Schematic diagram of the stimuli and task 119
5.2 Screenshot of the task instructions 121
5.3 Results from Experiment 5 123
5.4 Development of threshold and priming effect with age . . . 124

6.1 Audiometric data for participants in Experiment 6 131
6.2 Training study protocol 132
6.3 Baseline SRTs for young adults and older adults 136
6.4 Scatter plots of hearing ability and SRTs 137
6.5 Changes in SRTs during control period 137
6.6 Scatter plots of beat perception and masking release 139
6.7 Changes in SRTs during training period 140
6.8 Scatter plots of outcomes and trained skills 141
6.9 Scatter plots of improvements and baseline scores 143
6.10 Changes in SRTs during the retention period 145
6.11 SRT in steady noise at the four time points 145
6.12 SRT in modulated noise at the four time points 146
6.13 Confidence intervals for SRT in steady noise 147
6.14 Confidence intervals for SRT in modulated noise 147

List of Tables

1.1 Summary of musical training studies 4
1.2 Summary of endogenous and exogenous cueing methods . . 10

3.1 Test battery used in Experiment 1 59
3.2 Sensitivity and reliability of the matrix test with different maskers 63
3.3 Correlations between predictor variables 65
3.4 Correlations between predictors and speech thresholds . . . 67
3.5 Partial correlations between predictors and speech thresholds 68

4.1 Speech perception results from Experiment 2 85
4.2 Performance for individual target words in Experiment 2 . . 87
4.3 Tone detection results from Experiment 2 88
4.4 Summary of priming effects in Experiment 2 90
4.5 Comparison of priming effects for speech perception in Experiments 2 and 3 103
4.6 Summary of priming effects for the tone-detection task . . . 104
4.7 Comparison of priming effects for tone detection in Experiments 2 and 3 105
4.8 Correlations between beat perception and priming effects . 106

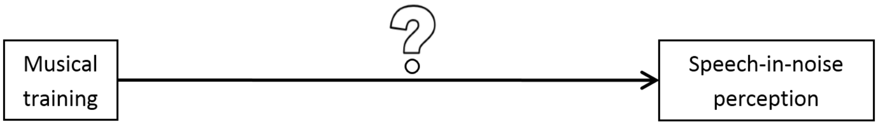
5.1 Participant data for the three age groups 118
5.2 Mean thresholds for each age group 123
5.3 Summary of priming effects in Experiment 5 123

6.1 Test battery for baseline assessment 132
6.2 Test battery for subsequent assessments 133
6.3 Baseline SRTs for young adults and older adults 136
6.4 Correlation coefficients for hearing ability and SRTs 137
6.5 Changes in variables during control period 138
6.6 Regression model for masking release 139
6.7 Changes in variables during training period 140

6.8 Correlations between outcomes and trained skills 141
6.9 Correlations between training-related changes 143
6.10 Regression model for threshold improvement 143
6.11 Changes in variables during retention period 144

CHAPTER 1

Introduction



Understanding speech amid background noise is a challenging task that causes difficulty for many people, especially young children and older adults. Musicians, on the other hand, may have an enhanced ability to perceive speech in noise. This chapter examines the skills needed for successful speech perception in noise, and outlines the approach taken in this thesis to investigate the potential of musical training as an intervention to help people who struggle to communicate in complex auditory environments.

1.1 Musical training and speech perception

1.1.1 Musicians as expert listeners

Learning to play a musical instrument is a complex, multisensory experience which engages multiple neural networks (Moreno and Bidelman, 2014). Musicians spend considerable amounts of time honing their skills and learning to appreciate acoustical features in music. This intense focus on auditory perception means that musicians can be excellent candidates for research into how the expert listening brain processes sounds. Musical training also provides an ideal model for neural plasticity – i.e., changes in the brain due to experience – and structural and functional differences have been observed in musicians compared to non-musicians (for reviews see, e.g., Moreno and Bidelman, 2014; Pantev and Herholz, 2011).

There is a large and growing body of literature based on this premise, comparing highly trained musicians with non-musicians. Behavioural advantages of musicianship have been reported for a variety of auditory perceptual skills, including: spectral resolution (Micheyl et al., 2006; Strait et al., 2010), temporal resolution (Rammsayer and Altenmüller, 2006; Strait et al., 2010), pitch processing (Magne et al., 2006; Schön et al., 2004), rhythm perception (Rammsayer and Altenmüller, 2006), and concurrent sound segregation (Zendel and Alain, 2009).

The particular promise of musical training as a possible intervention stems from the fact that musician advantages are not limited to musical tasks. For example, musicians demonstrate enhanced pitch processing ability in both musical and speech contexts (Magne et al., 2006; Schön et al., 2004), and also outperform non-musicians on cognitive tasks such as verbal working memory (Chan et al., 1998; Ho et al., 2003; Jakobson et al., 2008).

At this point it is important to note that, while group comparisons have provided a wealth of avenues for further research, these studies cannot conclusively reveal if musical training caused the observed enhancements. It could be argued that people with superior auditory processing abilities are more likely to take up and persevere with musical training, and that the groups are therefore self-selecting. Other pre-existing differences between the groups could also confound the results, such as socio-economic status – musical training is an expensive hobby – or personality traits – to reach a high level, self-motivation would be a key factor (see Corrigall et al., 2013).

To address this issue of causality, the next section considers studies which used an intervention paradigm to compare pre- and post-training performance in order to directly evaluate the impact of musical training.

1.1.2 Evidence from musical training studies

There is evidence of neural plasticity as a direct result of musical interventions. In one study, a group of young children received fifteen months of keyboard training while a control group – who were matched in terms of age, gender and socio-economic status – received no training (Hyde et al., 2009). Prior to the training, there were no group differences in brain or behavioural measures. Fifteen months later, the trained group showed structural plasticity in auditory and motor areas of the brain which correlated with improvements in behavioural measures of auditory and motor musical skills (Hyde et al., 2009). Comparing the trained children to an untrained control group allowed the authors to conclude that the changes were above and beyond what would be expected from normal development.

In another study, functional plasticity was observed after only two weeks of piano training (Lappe et al., 2008). Non-musician participants were randomly assigned to one of two training conditions: an auditory-motor condition which involved learning to play melodies on the piano; or an auditory-only condition which involved listening to the melodies and making judgements about them. The auditory-motor training resulted in greater improvements in both behavioural and neurophysiological measures of melody discrimination compared to the auditory-only training (Lappe et al., 2008). A subsequent study found a similar pattern of results for rhythm training (Lappe et al., 2011). These results suggest that the multimodal (i.e., sensorimotor) nature of music-making is an important component in the success of musical training for improving auditory perception.

Table 6.7 contains a brief summary of eight further studies which evaluated the impact of musical training on a variety of behavioural outcome measures. As shown in Table 6.7, significant improvements have been reported for a number of perceptual, cognitive and linguistic skills.

1.1.3 Proposed mechanisms of transfer from music to speech

1.1.3.1 Common processing

Music and speech are two complex forms of auditory signals which share some fundamental psychoacoustic properties. Both are created by combining basic elements according to a set of rules. Both convey important information via temporal rhythms and patterns of pitch changes over time. Both are subject to normalisation, i.e., words and melodies can be recognised regardless of the speaker or instrument.

It is reasonable to hypothesise that time spent training the auditory system to appreciate these features in music could lead to enhanced processing of the same features in speech (Besson et al., 2011; Patel, 2014; Shahin, 2011). For example, pitch processing is important for both music and speech, and transfer of musical training to speech perception has been observed for this skill (Moreno et al., 2009).

Table 1.1: Summary of musical training studies

Study details	Musical training programme
Children aged 6–15 (*n*=50); 1 year of training improved verbal (not visual) memory; control group discontinued training (Ho et al., 2003)	Established school orchestra programme; included instrumental lessons
Dyslexic children, mean age 8.8 (*n*=9); 15 weeks' training improved rapid auditory processing, phonological ability, spelling; 15-week control period (Overy, 2003)	Bespoke teacher-led training based on established methods; specific focus on rhythm and timing; 20-minute lesson, 3 days a week for 15 weeks
Children aged 8 (*n*=32); pseudo-random assignment; 24 weeks' training improved pitch discrimination in music and language, reading skills; compared to painting training (Moreno et al., 2009)	Teacher-led programme based on established methods; included rhythm, melody, harmony, timbre and form; 75-minute lesson, twice a week for 24 weeks
Children aged 4–6 (*n*=48); pseudo-random assignment; 4 weeks' training improved verbal intelligence, executive function; compared to visual arts training (Moreno et al., 2011)	Bespoke computerized programme led by teacher in classroom; primarily listening activities; included rhythm, pitch, melody, voice; two 1-hour lessons daily, 5 days a week for 4 weeks
Children aged 5–6 (*n*=41); random assignment; 20 weeks' training improved phonological awareness; compared to sports training (Degé and Schwarzer, 2011)	Bespoke programme based on established methods; included joint singing, drumming, dancing, rhythm, meter, pitch; 10-minute lesson, 5 days a week for 20 weeks
Children aged 8 (*n*=24); pseudo-random assigment; 1 year of training improved speech segmentation; compared to painting training (François et al., 2013)	Teacher-led music lessons based on established methods
Older adults aged 60–85 (*n*=31); random assignment; 6 months' training improved executive function, working memory; untrained control (Bugos et al., 2007)	Individual piano instruction; 30-minute lesson plus 3 hours practice each week for 6 months
Older adults aged 61–84 (*n*=29); assignment to music group based on motivation and availability; 4 months' training improved executive function, general mood; control group did other leisure activities (Seinfeld et al., 2013)	Teacher-led group piano lessons; bespoke for older adults; 90-minute lesson plus practice (45 minutes on 5 days) each week for 4 months

This concept of shared processing is a key feature in proposed transfer mechanisms (e.g, Besson et al., 2011; Patel, 2014), but it does not explain why musical training would improve processing beyond the level obtained through experience with speech perception.

1.1.3.2 Working memory as a mediating factor

Working memory has several related components (Baddeley, 2003), two of which are particularly relevant for the current research. The first involves the temporary storage and processing of information, i.e., it is not simply a storage system but also allows information to be manipulated in some way. For example, in the backwards digit span working memory task, participants must repeat back heard digits but in the reverse order, which requires the numbers to be held in memory while being reordered.

The second role of working memory is one of cognitive control, being responsible for executive functions such as allocating attention. The important point to note, here, is that working memory has a limited capacity. This means that performance on a cognitively demanding primary task will be impaired by the introduction of a concurrent memory task (Baddeley, 2003). Conversely, a primary task which is not cognitively taxing will be unaffected by the increased memory demands of a concurrent task.

As mentioned above, musicians have greater auditory working memory capacity compared to non-musicians (Chan et al., 1998; Ho et al., 2003; Jakobson et al., 2008) and musical training can lead to enhancements in working memory and executive function (Bugos et al., 2007; Ho et al., 2003; Moreno et al., 2011).

Kraus et al. (2012) suggested that auditory working memory is the key to transfer of learning from music to other domains. They proposed a model in which cognitive enhancement precedes and subsequently leads to fine-tuning of auditory processing. Consequently, the general improvement in auditory perception would apply to both music and speech (Kraus et al., 2012).

1.1.3.3 The OPERA hypothesis

Patel (2011) set out to explain not just *how* but also *why* musical training might enhance speech perception. His OPERA hypothesis proposed that transfer of learning from music to speech will occur for a given acoustic feature when five conditions are met:

> **O**verlap – the neural networks for processing the acoustic feature in music and in speech must overlap
>
> **P**recision – the level of precision of the acoustic feature required for successful musicianship must be greater than that needed for everyday speech perception
>
> **E**motion – musical training that activates the neural network must result in a positive emotional experience
>
> **R**epetition – musical training that activates the neural network must be repeated regularly
>
> **A**ttention – musical training that activates the neural network must involve focused attention on the acoustic feature

The overlap criterion implies shared processing as discussed above. However, with the precision criterion, the OPERA hypothesis goes one step further in attempting to explain why musical training might benefit speech perception. The final three criteria are based on factors which are known to encourage plasticity and which could certainly be assumed to apply to musical training (Patel, 2014). Music-making is an enjoyable activity, and it is likely that training exercises focusing attention on various aspects of music will be practised repeatedly until performance levels are reached.

Patel (2014) subsequently extended his OPERA hypothesis to include cognitive processes as well as acoustic features with the same five criteria. This allows for the possibility of auditory working memory as a transfer process, as suggested by Kraus et al. (2012).

1.1.4 Musical training for speech perception in noise

Having discussed the benefits of musical training and possible mechanisms by which learning could transfer to speech perception, the focus of this introduction now turns to the specific task of interest: speech perception in background noise.

Understanding speech in background noise is a complex task that causes particular difficulty for young children, older adults, and those with language disorders or hearing impairments (Pichora-Fuller et al., 1995;

Stuart, 2008; Ziegler et al., 2009). Communication is an important part of everyday life and it often takes place in less than ideal surroundings. Poor speech perception in noise can have negative consequences for education and social interactions (see Section 1.6). There are therefore many people who could potentially benefit from a training programme to improve speech perception in noise.

Outcomes of training are dependent on how well trainees comply with the programme (Chisolm et al., 2013). Compliance, in turn, depends on the participant's perceived benefit and enjoyment of the training (Tye-Murray et al., 2012). Feedback after one speech-based auditory training programme included a number of comments about the tedious and repetitive nature of some of the exercises (Tye-Murray et al., 2012), and Sweetow and Sabes (2010) reported that compliance was less than 30% for patients who were recommended a home-based auditory training programme.

Musical training could offer an enjoyable alternative – at least for people who have an interest in music – which could encourage compliance. In order to design a suitable musical training programme, it is first necessary to understand which skills are important for speech perception in background noise. The next sections will consider the sensory cues and cognitive processes which contribute to successful speech perception in background noise.

1.2 A brief introduction to auditory scene analysis

1.2.1 Setting the complex auditory scene

Imagine you are sitting in a crowded restaurant listening to your friend tell an anecdote. The couple at a nearby table are having a heated argument, and in the far corner a large group are celebrating a birthday. Jazz music is coming out of the speaker on the wall behind you; a clattering of plates and pans can be heard from the kitchen; and through the open window you can hear traffic noise from the busy street outside.

In a complex acoustic environment such as this, the information arriving at your ears at any given moment is a combination of sound waves from all the different sources. However, while your ears hear only a single mixture, you perceive the sounds as coming from separate sources spread around the room. You can identify these separate sources and choose to listen to your friend’s voice while ignoring the background noise.

This is a remarkable feat, and an important one given that much of our everyday communication occurs in less than ideal surroundings. In order to attend to a target signal, it is necessary to separate out sounds coming from different sources.

It is up to the brain to decode the combined information arriving at the ears in order to create an accurate perception of the auditory environment, via a process known as auditory scene analysis (Bregman, 1990).

1.2.2 Auditory scene analysis

In order to make sense of the auditory environment, the brain must partition simultaneous acoustic information into separate auditory objects. These auditory objects must also be grouped sequentially into streams from each sound source as the signals unfold over time (Bregman, 1990).

Bregman (1993) outlined how environmental regularities can be utilised to separate a waveform into auditory objects from different sources:

> *Temporal* – sounds from a single source have synchronised onsets and offsets, whereas sounds from two different sources are unlikely to start and stop at the same time. If two sounds in the mixture are asynchronous or overlap in time, these will be attributed to different sources.
>
> *Spectral* – many environmental sources (including voices and musical instruments) produce harmonic sounds, meaning that their component frequencies are multiples of a single fundamental frequency. If the mixture contains subsets of frequency components which are multiples of two different fundamentals, these subsets are likely to be attributed to different sources.
>
> *Spatial* – simultaneous sounds from a single source originate at the same location. If sounds are spatially separated, then they are likely to be perceived as coming from different sources.

Each of these cues can be unreliable in certain situations. For example, sounds from different sources might occasionally be synchronised in time; harmonic frequencies will not help to group noisy (inharmonic) sounds; spatial information is not as useful in reverberant rooms. In combination, however, there is sufficient redundancy that variations in the reliability of individual cues do not necessarily affect perception in realistic environments (Bregman, 1993).

Rules of environmental regularity also apply to the sequential grouping of objects into streams, although the emphasis here is on how properties change over time (Bregman, 1993):

> *Temporal* – sounds, or sequences of sounds, from a single source tend to either remain constant or change gradually. A sudden change in frequency, intensity or location will be interpreted as the onset of a new acoustic event from a different source.
>
> *Spectral* – a change in acoustic properties affects all components of an auditory object in the same way. Frequency components with differing patterns of change will be assigned to different auditory streams.

In summary, successful auditory scene analysis relies on the auditory system's ability to differentiate spectral and temporal properties of sounds in order to segregate and group auditory objects.

This passive, bottom-up (i.e., stimulus-driven) processing is not the whole story, however. A listener will often want to focus on a particular auditory stream, while ignoring irrelevant sounds, and this requires active, top-down attentional control.

1.3 Selectively attending to target speech

Selective attention is the process by which a subject focuses on a specific target object or characteristic and ignores task-irrelevant distractor stimuli. This section introduces some basic concepts connected to selective attention, before discussing some cues that can help to focus attention on a target speech signal.

1.3.1 Endogenous and exogenous cues

Attention can be oriented using either salient cues which automatically capture attention (exogenous) or symbolic cues which rely on the participant voluntarily orienting attention in response to instructions (endogenous).

Posner (1980) developed a visual cueing paradigm to orient covert spatial attention. The term ‘covert’ refers to the fact that participants maintain central fixation while attention is cued to the left or right in their peripheral vision. Overt spatial attention, by comparison, involves eye movements towards the attended location.

In this paradigm, a target stimulus is preceded by a cue, which is either a centrally presented arrow (endogenous) or an abrupt-onset stimulus presented in one of the possible target locations (exogenous). Performance on the task (measured by reaction times or accuracy of perceptual judgements) is compared for trials in which the cue correctly predicts target location (valid) and for trials in which the cue is misleading (invalid) or uninformative (neutral).

This method has been used to demonstrate that both endogenous and exogenous orienting of attention result in enhanced performance, but there are some important differences between the two types of cue (see Table 1.2). For example, since endogenous attention must be deliberately oriented by the participant in response to a symbolic cue, these cues must be valid in the majority of trials or the participant will realise that the cues are not helpful for the task and may stop using them altogether (Wright and Ward, 2008). Conversely, exogenous cues are so salient that orienting persists even when the participant is instructed to ignore them.

Table 1.2: Summary of the main properties of endogenous and exogenous orienting of visual covert spatial attention (Egeth and Yantis, 1997; Posner, 1980; Wright and Ward, 2008)

Type of orienting	Cue properties	Participant task	Time course
Endogenous (voluntary, active, goal-directed, top-down)	Symbolic cues presented at fixation; majority of trials must have valid cues	Participant must intentionally orient attention; reduced benefit observed in dual-task designs	Builds to peak 300 ms after cue; can be maintained for longer periods
Exogenous (automatic, passive, stimulus-driven, bottom-up)	Salient cue in to-be-attended location; difficult to ignore and need not be predictive	No need for compliance; benefit not affected by concurrent working memory demands	Peaks 100 ms after cue; dissipates quickly unless endogenous attention engaged

Another important distinction between endogenous and exogenous orienting is the differential reliance on working memory resources.

Since endogenous cues require deliberate orienting of attention by the participant, this process depends on working memory and is therefore impaired by a concurrent working memory task. Conversely, exogenous orienting happens automatically without the need of cognitive control, and is therefore impervious to concurrent memory demands (Wright and Ward, 2008).

1.3.2 Attending to location

Early investigations into selective attention used a dichotic listening paradigm, in which different spoken messages were presented to each ear simultaneously. Listeners were asked to shadow the message presented to one ear – i.e., to repeat it back quickly and accurately – while ignoring the message presented to the other ear (Cherry, 1953). Participants were able to fully focus attention on the target ear, to the extent that they could not recall any of the unattended message and even failed to notice if it switched language part way through (Cherry, 1953). Changes in spectral features of the ignored message were observed, however, with listeners able to identify when the unattended voice was switched from male to female, or was replaced by a pure-tone signal (Cherry, 1953).

A subsequent study reported that listeners often remembered noticing their own name in the unattended message (Moray, 1959); a phenomenon which has been dubbed the ‘cocktail party effect’. This is an example of an exogenous cue, which captures attention despite the listener’s focus being endogenously oriented to the target message. It has been shown that listeners with high working memory capacity are less likely to notice their name being presented in the unattended ear (Conway et al., 2001), demonstrating the link between working memory capacity and attentional control, or more specifically the ability to ignore distracting stimuli.

The dichotic listening studies demonstrated that selective attention can successfully be focused on one ear while ignoring the other. However, in everyday situations, it is unlikely that a target message will be heard in only one ear with all the background noise in the other ear. It is more likely that both ears will receive a mixture of target and noise.

More recently, investigators have manipulated the spatial configurations of target and masker speech in order to examine listeners’ ability to selectively attend to a single location.

The Coordinate Response Measure (CRM; Bolia et al., 2000) has often been employed for such a purpose. It is a speech corpus in which all sentences take the same form, e.g. 'Ready, Baron, go to red five now'. Participants listen out for a specific call-sign (e.g., 'Baron') in order to identify the target sentence, and then report the colour and number heard. There are 32 possible colour–number combinations (4 colours; 8 numbers). One or more masking sentences – with different call-signs, colours and numbers – are played concurrently with the target.

When the target sentence and a masker sentence are spoken by the same person and are presented from the same location, this task is extremely difficult. Brungart (2001) reported that performance in this condition was around chance level, and that the majority of incorrect answers were in fact the colour or number which appeared in the masker sentence. This suggests that listeners were able to segregate the concurrent sounds to correctly form individual words, but they were unable to attribute the words to the correct stream in the absence of further cues to aid attentional focus.

Spatial separation of the target and masker provides a perceptual benefit compared to the condition in which they are colocated. This is referred to as spatial release from masking. Figure 1.1 shows an example set-up for this type of experiment. Multiple sound sources are placed equidistant from the participant, along their audiovisual horizon, so that a speaker at 0° azimuth would be directly in front of the participant's head.

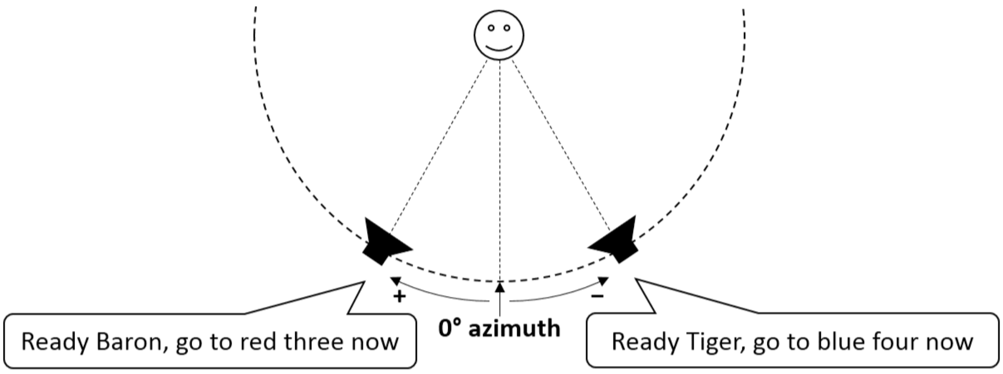

+
−
0° azimuth
Ready Baron, go to red three now
Ready Tiger, go to blue four now

Figure 1.1: Example configuration for a selective attention experiment using the Coordinate Response Measure

For a CRM task with two male speakers, a separation of just 10° (i.e., sources at ±5° azimuth) was enough to boost performance to about 90% correct (Brungart and Simpson, 2007, Figure 4).

Allen et al. (2008) measured spatial release from masking using two masking sentences which were presented either colocated with the target (at 0° azimuth) or ±30° azimuth. Performance was measured in terms of the speech reception threshold (SRT), i.e., the signal-to-noise ratio for which performance equals 50%. There was significant spatial release from masking, with a 12 dB improvement in threshold for the separated compared to the colocated condition.

A third condition was also investigated, in which the maskers were initially separated from the target but subsequently moved to be colocated. In this condition, spatial cues were available during identification of the target sentence (i.e., when the call sign was heard) but not during presentation of the two key words. Performance for this condition was significantly better than for the fully colocated condition, with a 3.6 dB improvement in threshold. The authors suggested that the initial spatial separation afforded allocation of attention to other characteristics of the target voice, which enhanced ongoing streaming even after colocation of the maskers (Allen et al., 2008).

1.3.3 Attending to voice characteristics

When the target and masker sentences are spoken by different people (but still colocated), characteristics of the target voice can be used to aid attention and enhance streaming. Figure 1.2 shows data from two studies which demonstrate this phenomenon. In each case, the data shown are from the condition in which target and masker sentences were presented at the same intensity level (i.e., at a signal-to-noise ratio (SNR) of 0 dB), meaning that level differences could not be used as an attentional cue (Brungart, 2001).

Brungart (2001) compared conditions in which the masker was spoken by the same person as the target, or a different person of the same gender, or someone of the opposite gender. Comparing the scores for these conditions (black triangles on Figure 1.2) demonstrates that greater differences in voice characteristics (e.g., fundamental frequency) correspond to improved performance on the task.

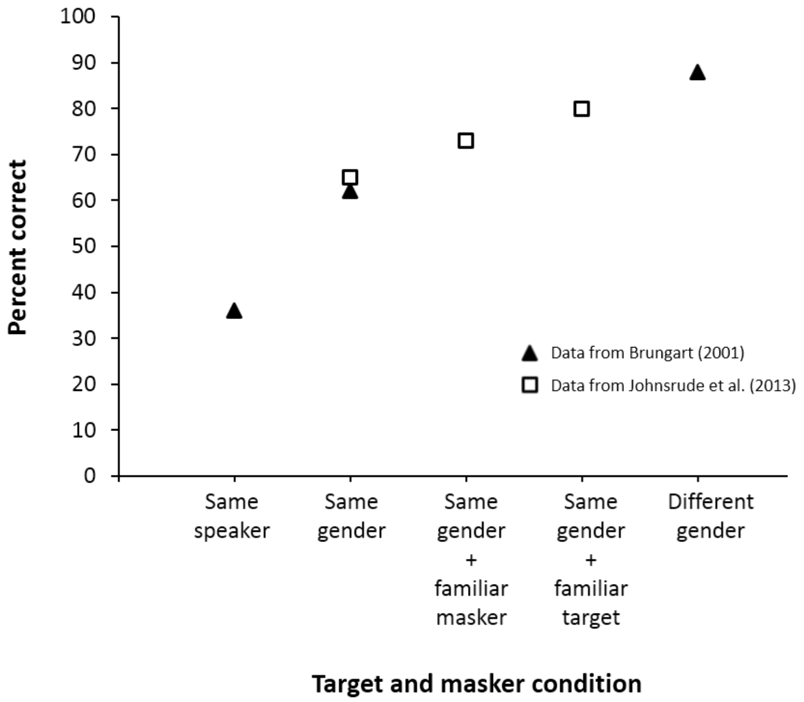


Figure 1.2: Performance on the CRM task under different target and masker conditions. Plotted using data from Figure 1 of Brungart (2001) and Figure 2 of Johnsrude et al. (2013)

Johnsrude et al. (2013) investigated the hypothesis that people would be better at distinguishing a voice that they had had a lot of experience listening to. Each participant's spouse was used for either the target or the masker sentence (or neither), while other sentences were spoken by unfamiliar voices of the same gender. The data (white squares on Figure 1.2) show a significant benefit for listening to a familiar voice, and also for ignoring a familiar voice, compared with unfamiliar voices.

Together these results show that differences between the target and masker voices, including acoustic characteristics and prior familiarity, can be exploited in order to selectively attend to a target voice and improve perception.

1.3.4 Selective attention is limited by sensory processing

It is important to note that selective attention can only be employed when the sound sources are perceptually separable (e.g., Brungart and Simpson, 2007; Cherry, 1953). If sensory processing is insufficient for successful auditory streaming, then the listener will be unable to focus attention on a single source. This was evident in an early experiment by Cherry (1953).

Two recordings of the same speaker were mixed and presented concurrently to the subject. The listener found it extremely difficult to separate the messages, and required many repetitions of the stimuli in order to identify phrases from one of the messages (Cherry, 1953).

Similarly, in the CRM study mentioned above, when target and masker sentences were colocated and spoken by the same voice, listeners performed at chance level and often reported the colour or number from the masker sentence (Brungart and Simpson, 2007). This signifies successful formation of auditory objects, but a breakdown in the sequential streaming of the two sources, which prevents attention being focused on the target sentence.

These are extreme examples, of course, as a single person cannot simultaneously speak two different messages. However, it highlights the primary importance of sensory processing for understanding speech in background noise, and goes some way to explaining why some people – e.g., those with hearing loss – struggle with speech perception in complex auditory environments. This will be discussed in more detail in Section 1.6 below.

In summary, as with the segregation and sequential organisation of sounds via auditory scene analysis, there are multiple cues that can be used to selectively attend to a target stream. Successful stream selection therefore relies on the listener's ability to differentiate the target voice on the basis of these cues, and to focus attention accordingly. Furthermore, the ability to selectively attend to a target and ignore distracting noises is associated with working memory capacity.

Even with a range of available cues, it will not always be possible to parse out a perfect signal from background noise, and some parts may be completely masked. However, in the case of speech, understanding is often robust even when the signal is degraded, and cognitive strategies can compensate for gaps in the signal, as described in the next section.

1.4 Reconstructing a degraded or incomplete speech signal

When listening to speech in quiet conditions, there is considerable redundant information in the signal. For example, speech recognition can be achieved using primarily temporal cues when spectral information is severely degraded (Shannon et al., 1995). This inherent redundancy means that speech perception can withstand considerable signal degradations such as those caused by interfering background noise.

Even with such a robust signal, there may still be parts of the speech which are completely masked by noise. Fortunately, there are other characteristics of speech which can be exploited to reconstruct the signal.

Speech sounds are often influenced by preceding or subsequent sounds, via coarticulation. If part of the speech is not heard due to noise, then coarticulatory cues from neighbouring sounds might help to fill in the gap. In fact, conversational speech can be understood even when periodic silences replace parts of the signal, as long as the frequency of these deletions is greater than 10 Hz (i.e., with silences of no more than 50 ms; Miller and Licklider, 1950).

1.4.1 The role of linguistic knowledge

Even when coarticulatory information is not available, listeners can still perceive a complete speech signal when part of a word has been completely replaced by noise (Warren et al., 1970). This phenomenon is known as phonemic restoration and it relies on linguistic knowledge. For example, when the replaced phoneme was the first ‘s’ in the word ‘legislatures’, no other phoneme would produce a meaningful word. In this case, participants heard the complete word and perceived the noise to occur at another point in time (Warren et al., 1970).

When there is ambiguity in the missing phoneme, i.e., when several alternatives are possible, perception is influenced by the sentence context (Warren et al., 1970). This demonstrates another source of redundancy in speech which results from linguistic constraints. The rules of language dictate syntactic structure which in turn allows predictions to be made about upcoming word types (e.g., verb or noun). Semantic context also provides information about which words are most likely to occur in order for the sentence to have meaning.

Semantic information was manipulated in the development of the Speech in Noise test (SPIN; Kalikow et al., 1977) which includes both low-context and high-context sentences for each target keyword. Identification of the final word is significantly easier when semantic context is provided (high-context) than when no such clues to the meaning of the target word are available (low-context), demonstrating the importance of semantic context when listening to speech in challenging conditions.

Linguistic cues can be used to make predictions about upcoming words and can also be used to fill in parts of the signal that were unable to be separated from the background noise. This process relies on auditory working memory, since the degraded signal must be stored and replayed while contextual constraints are applied.

Zekveld et al. (2007) developed a visual analogue for this process of linguistic closure, wherein written text is partially obscured by black bars. The amount of masked text is varied adaptively to find the point at which performance equals 50%, called the text reception threshold (TRT). When the same sentence stimuli are used for both visual and auditory tests, the shared variance of the text reception threshold (TRT) and speech reception threshold (SRT) can be interpreted as the contribution of domain-general linguistic and cognitive abilities. Zekveld et al. (2007) reported a shared variance between the tests of about 30%, even after controlling for age.

1.4.2 Listening to speech in modulated noise

For a background noise that remains at a constant level, the masking of speech sounds will be relatively uniform over time. In everyday listening, it is more common to experience background noise which fluctuates in intensity. The resultant fluctuations in signal-to-noise ratio allow for additional information to be gleaned from the 'dips' in the noise, i.e., those times when the noise level drops and the speech can be heard more clearly (e.g., Gnansia et al., 2008; Gustafsson and Arlinger, 1994; Miller and Licklider, 1950).

The benefit for speech perception in amplitude-modulated noise compared with steady noise is known as modulation masking release, and it varies with the depth (Gustafsson and Arlinger, 1994; Gnansia et al., 2008) and frequency (Füllgrabe et al., 2014; Gustafsson and Arlinger, 1994; Miller and Licklider, 1950; Rhebergen et al., 2006) of the modulation. Masking release increases with increasing depth of modulation (Gustafsson and Arlinger, 1994; Gnansia et al., 2008), and this holds even when the steady and modulated noises are equated in terms of overall intensity (root-mean-square level). The increased benefit gained from deeper dips in noise (i.e., higher SNRs for glimpsing) offsets any disadvantage from greater peaks in noise where speech may be completely masked.

Maximal masking release has been observed for modulation frequencies between 8 and 20 Hz (Füllgrabe et al., 2014; Gustafsson and Arlinger, 1994; Miller and Licklider, 1950; Rhebergen et al., 2006). At lower frequencies, extended periods of high intensity noise mean that larger portions of speech (e.g., whole words) will be completely masked. This impedes reconstruction of the signal, despite facilitating speech perception in the corresponding extended periods of low intensity noise.

Conversely, at higher frequencies, the opportunities for dip listening will be shorter and good temporal resolution will be required to gain the maximum information from these periods (Dubno et al., 2002). Once a partial signal has been gleaned from the dips, linguistic cues and working memory can be used to restore missing parts of the speech as discussed above.

1.5 The importance of temporal information in speech

A speech signal unfolds over time and its temporal structure is important for comprehension. When temporal information is degraded, there is a corresponding reduction in speech intelligibility (Drullman et al., 1994a,b). Conversely when temporal cues are preserved, speech can be intelligible even when very little spectral information is available (Shannon et al., 1995).

Syllable rate is also important for perception, and time-compressed signals lead to reduced intelligibility Ghitza and Greenberg (2009). By increasing the syllable rate three-fold, the intelligibility of the speech was greatly reduced. Silent intervals of either equal or varied lengths were then inserted into the compressed signals. Intelligibility was highest when the original syllable rate was restored by inserting equal-length silences, thereby recreating the rhythmic information from the original speech signal (Ghitza and Greenberg, 2009).

Together these results suggest that rhythmic information contained in the temporal envelope is useful for understanding speech. Given the importance of rhythmic information for speech intelligibility, a number of authors have proposed a role for prediction in models that could apply to the perception of speech in challenging listening environments (Elhilali et al., 2009; Schroeder et al., 2008; Zion Golumbic et al., 2012). If target onsets can be predicted, then listeners can orient attention to those time-points in order to enhance processing.

1.5.1 Orienting attention in time

As described in Section 1.3, cueing methods for endogenous and exogenous orienting of attention have been clearly defined and explored in visual spatial attention. However, the focus here is on orienting temporal attention during an ongoing auditory signal. Just as spatial attention refers to the orienting of attention to a point in space, temporal attention refers to the orienting of attention to a point in time. The next sections will consider how the concepts of endogenous and exogenous attention apply to auditory temporal attention.

1.5.1.1 Endogenous orienting of attention to points in time

Auditory attention can be oriented cross-modally using visual cues. In one study, lights above loud speakers were used to indicate when and/or where a target signal would appear (Best et al., 2007b). When a light cue indicated either the spatial location or the time interval, identification accuracy was improved in comparison to a no cue condition. When a combined cue provided both the target location and time interval, performance was further enhanced, suggesting an additive effect of spatial and temporal orienting of attention.

Another technique to orient temporal attention is to train participants to expect the target at a certain point in time. If an auditory cue precedes the target by a fixed interval on the majority of trials, then listeners will come to expect the target after this time interval. Task performance for targets at the expected time can then be compared to that for infrequent early or late targets. This method has been used to demonstrate that temporal attention enhances detection of pure-tone targets in both forward-masking (target preceded by narrowband noise; Wright and Fitzgerald, 2004) and simultaneous-masking (target presented in broadband noise; Werner et al., 2009) paradigms.

These cueing methods are comparable to the endogenous cueing paradigm described above for orienting visual spatial attention. They use symbolic or learnt cues to instruct participants when to attend, and the majority of trials have valid cues. Any benefit for validly cued targets is reliant on deliberate control of attention by the participant, and as a consequence the effect is diminished by a concurrent working memory task (Capizzi and Correa, 2012). In other words, the concept and methods of endogenous cueing apply equally well to both spatial and temporal attention.

1.5.1.2 *Exogenous orienting of attention via rhythmic priming*

In spatial attention, an exogenous cue is a stimulus which precedes the target in the to-be-attended location and is salient enough to automatically capture attention. It has been suggested that an abrupt-onset stimulus also draws attention to its temporal locus, via 'reactive attending' (Jones et al., 2002). However, for the purposes of the current thesis, it is more relevant to consider orienting temporal attention to future events, via 'anticipatory attention' (Jones et al., 2002).

Auditory anticipatory attention can be oriented via rhythmic regularities in a priming sequence. According to dynamic attending theory (Jones and Boltz, 1989; Large and Jones, 1999), attention will automatically entrain to an external rhythmic stimulus so that peaks in attention coincide with predicted onsets in the ongoing rhythm. Stimuli which match these expectations will therefore benefit from enhanced processing compared to those which do not align with expected onsets (see Figure 1.3).

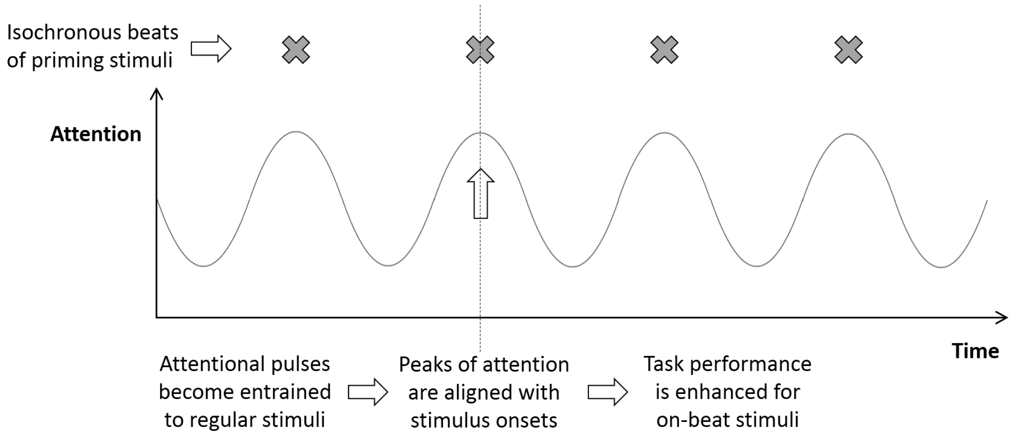

Isochronous beats of priming stimuli
Attention
Time
Attentional pulses become entrained to regular stimuli
Peaks of attention are aligned with stimulus onsets
Task performance is enhanced for on-beat stimuli

Figure 1.3: Illustration of dynamic attending theory: an external rhythmic stimulus drives anticipatory attention in order to orient temporal attention to predicted future onsets (Jones et al., 2002)

There is a growing body of evidence in support of dynamic attending theory. Jones et al. (2002) were the first to demonstrate that rhythmic priming can enhance auditory processing for non-temporal tasks. Participants were required to compare the pitch of a standard and a comparison tone which were separated by an isochronous (equally spaced in time) sequence of tones. When the comparison tone occurred on the next beat of the sequence, performance on the pitch task was better than when the comparison tone occurred between beats. The performance profile was quadratic in shape, centred around the on-beat position, consistant with a peak in anticipatory attention in line with the beat of the sequence (Figure 1.3). To test the assumption that entrainment persists beyond the end of the external stimulus, the experiment was repeated with targets presented on or around the next but one beat of the sequence. As predicted, a similar performance profile was obtained: quadratic in shape with peak performance for on-beat targets. Finally, when an irregular (i.e., no isochronous beat) priming sequence was used, the expectancy profile was flatter, without the characteristic quadratic trend associated with peaks in anticipatory attention Jones et al. (2002).

Rhythmic priming effects have also been shown to enhance perception of speech targets in quiet. A musical rhythm sequence was used to prime expectations in a phoneme detection task, and reaction times were shorter for on-beat compared to late targets (Cason and Schön, 2012).

The beneficial effects of rhythmic priming do not rely on deliberate orienting by participants; in fact, they persist even when participants are instructed to ignore the priming stimuli (Bolger et al., 2013; de la Rosa et al., 2012; Jones et al., 2002). The process is also unaffected by a concurrent working memory task (de la Rosa et al., 2012), suggesting that rhythmic priming does not place high demands on cognitive control. In these respects, rhythmic priming is comparable with the classic exogenous cueing paradigm (see Table 1.2).

One way in which the paradigms diverge is in the apparent temporal specificity of exogenous predictive orienting in the auditory domain. In one study, Rimmele and Sussman (2011) compared the effects of implicit temporal and spatial orienting in audition. The stimuli consisted of a moving sequence of 12 tones, followed by a burst of white noise and then a final tone. The final tone was either a target (complex tone) or a non-target (pure tone) and participants were required to respond as quickly as possible only to target stimuli. Temporal regularity in the tone sequence resulted in faster and more accurate responses, while spatial predictability provided no behavioural benefit for the go/no-go task (Rimmele and Sussman, 2011).

1.5.2 Rhythmic priming during speech listening

In an early study, Meltzer et al. (1976) manipulated the timing of phoneme targets in a sentence context such that they could occur early, on-time or late with respect to the target's original position in the unaltered sentence. When targets were temporally displaced, listeners were slower to react than when the target coincided with the on-time position (Meltzer et al., 1976). This suggests that listeners do form temporal predictions to orient attention during speech listening. There is also some evidence that listeners orient temporal attention to word onsets when listening to narrative speech (Astheimer and Sanders, 2009).

While speech does not necessarily contain a strictly isochronous beat, it does make use of acoustic emphasis, and the pattern of stressed and unstressed syllables – referred to as meter – creates a sense of rhythm. In fact, listeners perceive regularity even when the speech signal does not contain strict isochrony (Schmidt-Kassow and Kotz, 2009). Listeners can also tap along to the pattern of stressed syllables, just as they would tap along to the beat in music (Lidji et al., 2011).

It has been suggested that listeners use this rhythmic metric structure to orient attention towards stressed syllables, and that attention 'bounces' from one stressed syllable to the next (the attentional bounce hypothesis; Pitt and Samuel, 1990).

To investigate this hypothesis, Pitt and Samuel (1990) used a phoneme-detection task and compared performance for neutral-stress targets in syllables which were predicted to be stressed with those in syllables which were predicted to be unstressed. When the targets were embedded in a sentence context, fewer errors were observed for predicted-stress targets, but there was no significant difference in reaction times. In a second experiment, lists of disyllabic words – with matching stress patterns (either weak–strong or strong–weak) – were used to create a stronger sense of alternating stress. Reaction times were significantly shorter for targets occurring in predicted-stress syllables (Pitt and Samuel, 1990).

A similar paradigm, with phoneme targets embedded in lists of disyllabic words, was used by Quené et al. (2005). An additional manipulation was applied so that the temporal intervals between stressed syllables were either identical (isochronous rhythm) or jittered. Reaction times to a phoneme target were significantly shorter for the isochronous compared to the jittered condition, suggesting that increased rhythmic regularity can improve speech perception (Quené et al., 2005).

Together these results support the idea that temporal attention is oriented towards stressed syllables. The benefit of anticipatory attention depends on the strength of the rhythmic information available in the speech context, and this can be enhanced via the use of predictable stress patterns and temporal regularity.

1.6 A lifespan perspective on speech perception in noise

Understanding speech in background noise is a complex process which relies on a variety of perceptual, cognitive and linguistic skills, as discussed above and summarised here:

> *Spectral resolution* – to separate concurrent sounds in terms of fundamental frequency or mistuned harmonics
>
> *Temporal resolution* – to separate auditory objects with asynchronous onsets/offsets; to take advantage of dip listening in modulated noise
>
> *Selective attention* – to aid streaming by focusing on properties of the target speech, such as voice characteristics or spatial location
>
> *Working memory* – to aid attentional control and inhibition of distractors; to store and replay the degraded speech signal while linguistic constraints are applied
>
> *Linguistic knowledge and experience* – to restore missing parts of the signal using coarticulatory cues, phonemic restoration, or syntactic or semantic context

The capacity to use all of these skills develops with age and experience, and there is great individual variation in speech perception in noise. The perceptual and cognitive skills develop at different rates during childhood and are also subject to age-related decline in older adulthood. Young children and older adults are therefore believed to be at a disadvantage when it comes to speech perception in noise (e.g., Pichora-Fuller et al., 1995; Stuart, 2008).

1.6.1 Development during childhood

For speech in quiet conditions, children reach adult levels of perception at around 8 years of age (Stuart, 2005, 2008). For speech in background noise, development depends on the masker (Nishi et al., 2010; Bonino et al., 2013) and in some conditions perception does not reach adult levels until about 14 years of age (Hall et al., 2012; Johnson, 2000; Stuart, 2008).

This is not surprising given the variety of perceptual, cognitive and linguistic skills that are required for successful speech perception in noise, all of which develop at different rates:

> *Spectral resolution* – reaches adult levels of performance by age 6 years (Hartley et al., 2000); younger children (5–7 years) require more spectral information than older children (10–12 years) for comprehension of degraded speech (Eisenberg et al., 2000)
>
> *Temporal resolution* – is still developing at age 11 years (Hartley et al., 2000; Stuart, 2005); modulation masking release is reduced in young children (4–6 years) compared to adults (Hall et al., 2012), but does not appear to improve with age for children aged 6–15 years (Stuart, 2008)
>
> *Working memory* – older children (10–12 years) have better auditory working memory than younger children (5–7 years) (Eisenberg et al., 2000)
>
> *Spatial release from masking* – young children (4–7 years) do benefit from spatial separation of target and masker, and the amount of masking release is similar to that experienced by adults (Litovsky, 2005)
>
> *Linguistic knowledge and experience* – young children (5 years) do benefit from linguistic context when age-appropriate language is used (Fallon et al., 2002)

In summary, children can benefit from spatial release from masking, modulation masking release, and linguistic context, but their perception of speech in noise is hindered by still developing sensory and cognitive systems.

1.6.1.1 Consequences of noisy classrooms

For children, much of their everyday communication takes place in a classroom environment. Understanding what the teacher is saying is crucial to the purpose of a classroom. Neuman et al. (2010) measured speech reception thresholds for sentences in background noise conditions which are typical of school classrooms. Speech thresholds improved as a function of age for normal-hearing children aged 6–12. Younger children (aged 6–8) performed worse than older children (aged 10–12) who in turn performed worse than adults (Neuman et al., 2010).

In a study of 8-year-old children, learning in a noisy classroom was associated with poor performance on tests of phonological processing, as well as higher annoyance levels and less favourable relationships with teachers and peers (Klatte et al., 2010). These results suggest that the ability to understand speech in background noise has an impact on academic achievement, social relationships, and the child's overall experience at school. For children with learning or language impairments, who often struggle to understand speech in noise (e.g., Ziegler et al., 2009), the detrimental effects of a noisy classroom may be considerable.

1.6.2 Decline during older adulthood

A recent large-scale population study reported subjective and objective hearing measures for adults aged 40–69 across the United Kingdom (Moore et al., 2014). Subjective reports of hearing difficulties increased linearly with age. Speech perception in noise declined exponentially with age, with a steeper rate of change after age 50. Performance on cognitive tests (including working memory and processing speed) also declined with increasing age, and these scores were related to speech perception thresholds (Moore et al., 2014).

These results are in line with previous reports that older adults struggle with speech perception in noise due to a combination of hearing loss and cognitive decline (e.g., Humes, 1996; Pichora-Fuller et al., 1995; Schneider et al., 2002).

People with hearing loss demonstrate impaired performance on tests of temporal resolution (George et al., 2007), speech perception in steady and modulated noise (George et al., 2007; Hall et al., 2012) and modulation masking release (Hall et al., 2012). For hearing-impaired listeners, audibility is the most important factor for speech perception in noise, although cognition does also play a part (Akeroyd, 2008; George et al., 2007).

Even those older adults with clinically normal hearing perform worse than younger hearing-matched controls on tests of speech perception in noise, which has been attributed to cognitive decline (Füllgrabe et al., 2014). In fact, for normal-hearing listeners, conclusions about speech perception in noise abilities appear to depend mainly on cognitive factors (Füllgrabe et al., 2014; George et al., 2007).

Older adults do, however, benefit as much as younger adults in terms of both modulation masking release and spatial release from masking (Füllgrabe et al., 2014). They also benefit from a lifetime's experience of listening to speech. While perception of an unfamiliar voice amid masking speech declines with increasing age, no age-related decline is observed when the target speaker is the listener's spouse (Johnsrude et al., 2013).

Pichora-Fuller et al. (1995) compared the performance of young normal-hearing adults, older normal-hearing adults, and older hearing-impaired adults using high and low context sentences in noise. In terms of overall performance, the younger adults did better than the older normal-hearing adults, who in turn did better that the older hearing-impaired adults. The interesting finding was that both groups of older adults achieved greater benefit from semantic context than did the younger adults (Pichora-Fuller et al., 1995).

The findings from Pichora-Fuller et al. (1995) suggest that older adults may rely on their linguistic experience to to fill in the extra gaps in a speech signal which result from perceptual impairments. Dependence on this compensatory mechanism appears to come at a price in terms of cognitive effort, as demonstrated by a concurrent working memory task combined with a speech perception in noise test (Pichora-Fuller and Souza, 2003). At challenging signal-to-noise ratios, Pichora-Fuller and Souza (2003) found that older adults could recall fewer words, suggesting that working memory resources were allocated to the processing of the degraded signal. This explanation is supported by the authors' clinical experience with older adults. Even those with normal hearing report that listening to speech in everyday situations requires a lot of effort and is therefore very tiring (Pichora-Fuller et al., 1995). For older adults with hearing loss, this problem will be compounded, as even in quiet a verbal memory task is impacted by the extra effort required to process auditory stimuli (McCoy et al., 2005).

In summary, age-related decline in auditory perception and cognitive ability leads to poorer speech perception in noise by older adults. A lifetime of linguistic experience can partially compensate for a degraded speech signal, but this requires additional cognitive effort. Everyday communication may become frustrating and tiring as a result, and this could lead to avoidance of social events and a decline in well-being (Schneider et al., 2002).

1.7 Musician advantage for speech perception in noise

Young children and older adults are two groups who could potentially benefit from a training programme to improve speech perception in noise. At the other end of the scale, musicians may have an advantage for speech perception in noise, the evidence for which is discussed in this section.

1.7.1 Evidence from group comparison studies

Given the evidence that musicians have enhanced perceptual and cognitive abilities related to auditory scene analysis (see Section 1.1.1), it follows that they should have an advantage when it comes to speech perception in noise.

The first direct evidence for a link between musical training and speech perception in noise was reported by Parbery-Clark et al. (2009). Young adult participants (aged 19–31) completed two sentence-in-noise tests: HINT (Nilsson et al., 1994) – which uses simple sentences in a steady speech-spectrum noise – and QuickSIN (Killion et al., 2004) – which uses more complex sentences in a babble masker.

Musicians outperformed non-musicians on both speech tests, demonstrating a significant musician advantage for speech perception in noise (Parbery-Clark et al., 2009). Performance on QuickSIN was correlated with years of musical training, suggesting a possible dose response. There was no difference between the groups for the easier

HINT condition in which the target sentence and masker were spatially separated. A similar musician advantage for QuickSIN and HINT was also found for older adults (45–65 years with normal hearing; Parbery-Clark et al., 2011).

These studies both reported statistically significant group differences, but the observed musician benefit for speech reception thresholds was small (<1 dB). Results from subsequent studies cast doubt on the reproducibility of a musician enhancement for speech perception in noise.

Zendel and Alain (2012) reported that older musicians showed less age-related decline for speech perception in noise (QuickSIN). However, no group difference is apparent for the younger adults in their Figure 4 (Zendel and Alain, 2012).

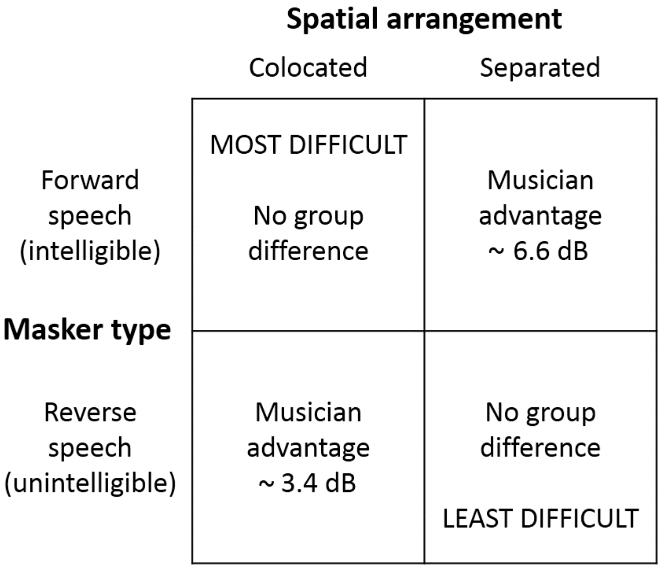
Ruggles et al. (2014) reported no group difference for musicians versus non-musicians on QuickSIN or HINT, despite using similar criteria for defining their groups as did Parbery-Clark et al. (2009). Similarly, no musician advantage was observed for perception of HINT-like sentences in a range of maskers: competing speech (different gender talker), rotated speech (unintelligible), speech-modulated noise, steady noise (Boebinger et al., 2015). Boebinger et al. (2015) reported that more than two hundred participants would be needed to find a significant group difference if the observed effect size was accurate.

A recent study aimed to elucidate the nature of any musician advantage for speech perception in noise (Swaminathan et al., 2015). By manipulating masker intelligibility and spatial separation, four test conditions were created which varied in difficulty and cognitive demands. The use of intelligible speech maskers and spatially separated sound sources was intended to be more ecologically valid than clinical tests such as HINT and QuickSIN.

In this study, target and masker sentences always took the form: [name] [verb] [number] [adjective] [object], with 8 possible options for each word. The target sentence was identified by use of the name 'Jane' (e.g., 'Jane took two new toys'), while the two masker sentences used different names.

The target and masker sentences were spoken by different female voices, which were randomly selected on each trial. The target always originated from straight ahead, while the masker sentences were either colocated with the target or separated by ±15° azimuth. The masker sentences were either presented forward (intelligible) or were reversed on a word-to-word basis (to make them unintelligible while maintaining speech-like amplitude modulation). See Figure 1.4 for a summary of the conditions and main findings from Swaminathan et al. (2015).

In the most difficult condition, where the maskers were intelligible and colocated with the target, performance was universally poor, with no group difference between musicians and non-musicians. Conversely, in the easiest condition (unintelligible maskers spatially separated from the target) all listeners performed well, again with no group difference. This is comparable to the spatially separated HINT condition for which no group difference was reported by Parbery-Clark et al. (2009). The other two conditions provided more interesting results.



	Spatial arrangement	
Masker type	Colocated	Separated
Forward speech (intelligible)	MOST DIFFICULT No group difference	Musician advantage ~ 6.6 dB
Reverse speech (unintelligible)	Musician advantage ~ 3.4 dB	No group difference LEAST DIFFICULT

Figure 1.4: Experimental conditions and results from Swaminathan et al. (2015)

When unintelligible maskers were colocated with the target, a significant musician advantage was observed (Swaminathan et al., 2015). This condition is comparable to QuickSIN which also uses a colocated modulated masker, but the threshold difference was greater than that previously reported by Parbery-Clark et al. (2009). It could be that the two reversed-speech maskers provided more frequent and deeper dips in which to glimpse the target, compared to the multi-talker babble used in QuickSIN. Success in this condition would therefore rely on both perceptual and cognitive skills to extract the target from the maskers and fill in the gaps in the signal, as discussed in Section 1.4.2. The thresholds in this condition showed greater individual variability compared to the easier spatially separated unintelligible masker condition.

When intelligible maskers were spatially separated from the target, musicians had an even greater enhancement in threshold and demonstrated significantly more spatial release from masking (Swaminathan et al., 2015). The authors considered this to be the most ecologically valid condition, similar to having a conversation while other people are talking nearby, and also cognitively demanding. As discussed in Section 1.3.2, spatial separation allows the listener to take advantage of voice characteristics in order to selectively attend to a target sentence (Allen et al., 2008). In this condition, masking sentences were intelligible, confusible with the target, and also spoken by female voices, making it crucial to take advantage of the spatial separation to succeed. This reliance on cognitive as well as perceptual abilities resulted in a large group difference and a wide range of individual variation among the non-musicians.

The findings of Swaminathan et al. (2015) add support to the idea of a musician enhancement for speech perception in noise, and suggest important considerations for future work in this field. Speech perception tasks should be sufficiently difficult (though not impossible) to place high demands on both perceptual and cognitive abilities in order to maximise individual variability and provide the best chance of observing group differences. The greatest difference was observed for spatially separated intelligible maskers, although the colocated unintelligible (modulated) masker condition also resulted in a significant musician advantage (Swaminathan et al., 2015). These two conditions are therefore good candidates for use in further research in this field.

1.7.1.1 Limitations of defining comparison groups

All of the studies discussed in the previous section involved comparisons between a group of musicians and a group of non-musicians. This approach has provided valuable insights into the brains and behaviours of musicians as expert listeners, as discussed in Section 1.1.1, but it is not without its shortcomings. The most obvious limitation is that it is not possible to infer causation from a cross-sectional design, as discussed above. However, there are also pitfalls associated with defining the comparison groups.

Defining 'musicians'

In each of the studies discussed above, participants were included in a musician group only if they met a number of strict criteria. For example, Parbery-Clark et al. (2009) defined musicians as those who started formal music training before age 7, had played for at least 10 years, and had continued to practise at least 3 times per week in the 3 years leading up to the study.

Although similar criteria were used to define the groups in each study, it is not clear which of these criteria might be sufficient for the question at hand. If all of these criteria are in fact necessary to observe a musician advantage for speech perception in noise, then it is unlikely that a short-term musical training programme – particularly one for older children or adults – would have the desired impact.

Despite the seemingly stringent criteria for musicians, there is one factor that has rarely been considered: the instruments they play. A comparison of percussionists, string players and non-musicians produced an interesting pattern of results for auditory tasks (Rauscher and Hinton, 2003). Percussionists outperformed non-musicians on duration discrimination, while string players outperformed non-musicians on frequency discrimination (Rauscher and Hinton, 2003). These results are perhaps not surprising given the nature of the two instrument groups: percussionists require precise timing perception while string players require precise pitch perception to tune their instruments.

The type of instrument also has an impact on the musician advantage for speech perception in noise. Drummers achieved significantly better thresholds for QuickSIN compared to non-musicians, with vocalists in between these groups (although not significantly different from either) (Slater and Kraus, 2015). Findings such as these confirm that caution should be exercised before assuming that results from group comparison studies will generalise to all musicians.

Defining 'non-musicians'

Non-musicians are often quite simply defined as having little or no formal musical training. For example, Parbery-Clark et al. (2009) selected non-musicians who failed to meet their musician criteria and had not had any musical training in the 7 years prior to the study.

The focus on formal instrument training doesn't take into consideration other musical experience which could contribute towards the development of musical ability. Self-taught instrumentalists, choral singers, or DJs, for example, could be counted as non-musicians as they might not have had formal training.

Another potential problem with group comparisons is that the musician advantage for speech perception in noise might be mediated by musical aptitude or ability rather than involvement in training. If this were the case, then the results could be confounded by 'musical non-musicians', i.e., people who have an aptitude for music but who have never pursued formal musical training. There would then be considerable overlap between the two groups, and this could explain some of the contradictory findings discussed above (e.g., Ruggles et al., 2014, Figure 3).

1.7.2 Evidence from a longitudinal training study

Slater et al. (2015) recently reported promising results from a longitudinal study looking at the impact of musical training on speech perception in noise. Participants (mean age 8.2 ± 0.7) were recruited from the waiting list of an established community music programme, which provides free access to musical training for children in low-income areas. After an initial assessment, the children were randomly assigned to two groups: one group started training immediately, while the other started after one year and therefore acted as a control group during the first year. A significant improvement in HINT threshold (2.1 dB) was observed after 2 years of musical training (Slater et al., 2015), and the final HINT threshold was correlated with the number of hours of instrument training.

No significant improvements in speech threshold were found for either group after their first year of training, although some individuals did show significant improvement after just one year (Slater et al., 2015). The authors discussed these findings in terms of the length of time needed for far transfer of skills from music to speech (Slater et al., 2015). It is worth noting, however, that the design of the music programme involved a comprehensive musicianship course of up to a year before children started instrumental lessons. It is therefore possible that transfer occurred more quickly than assumed, but after an initial delay.

The latter is a more encouraging explanation when considering a short-term intervention for improving speech perception in noise, and several studies have reported near and far transfer effects after relatively short musical training programmes (see Table 6.7).

Figure 1.5 summarises speech perception in noise across the lifespan: perception develops and later declines with age, while musician advantages have been observed for each age group.

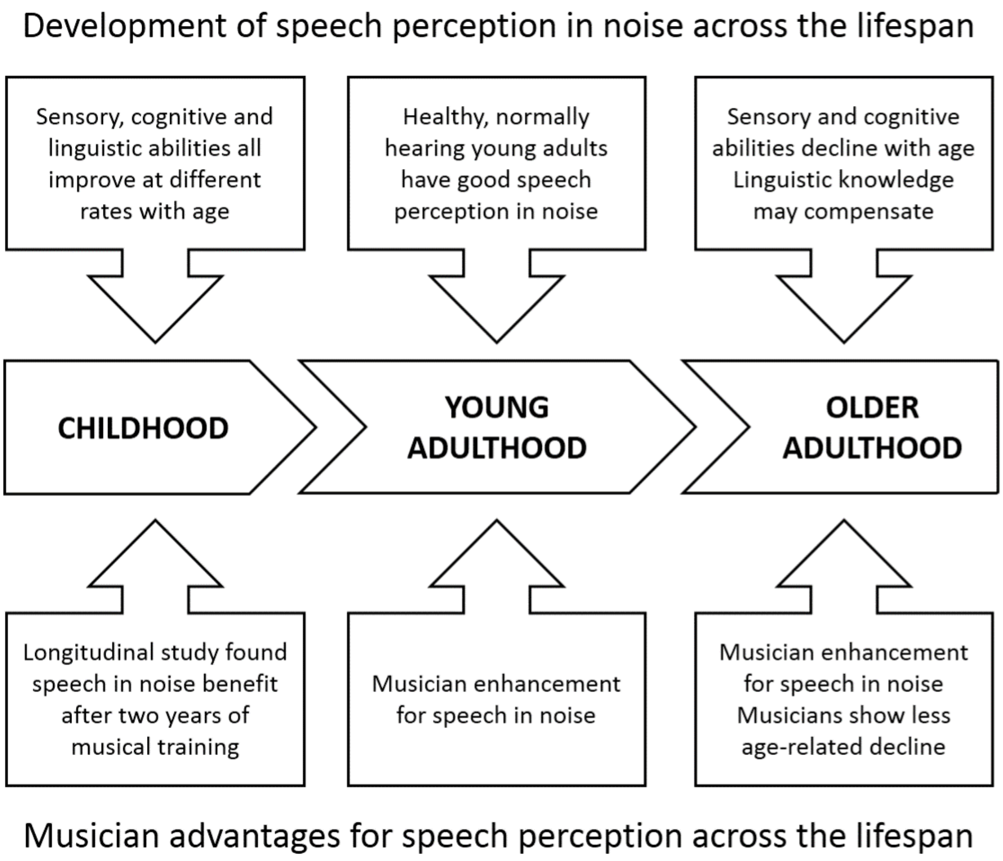

Development of speech perception in noise across the lifespan
Sensory, cognitive and linguistic abilities all improve at different rates with age
Healthy, normally hearing young adults have good speech perception in noise
Sensory and cognitive abilities decline with age Linguistic knowledge may compensate
CHILDHOOD
YOUNG ADULTHOOD
OLDER ADULTHOOD
Longitudinal study found speech in noise benefit after two years of musical training
Musician enhancement for speech in noise
Musician enhancement for speech in noise Musicians show less age-related decline
Musician advantages for speech perception across the lifespan

Figure 1.5: Development of speech perception in noise across the lifespan and through musical training

1.8 Designing a musical training programme

The studies in Table 6.7 provide some useful insight into different approaches to designing a musical training programme.

Most of the studies included instrumental lessons, either as the major focus of training or as a smaller part of classroom lessons, although Moreno et al. (2011) had some success using primarily listening activities. The training was generally quite time-intensive, involving lessons or practice on several days of the week. Although this is typical of musical training, it may not be practical as an intervention if it must be sustained over a long period. These studies are persuasive as an argument for including music education in schools or in residential homes for older adults, but it is not clear if such programmes would work for short-term rehabilitation.

One noticeable commonality among the training studies is that all but one attempted to recreate a comprehensive musical programme based on established methods, which encompassed a range of key skill areas such as rhythm, pitch, melody, timbre and sometimes musical theory. Such multifaceted training is time consuming, and likely contains elements which do not directly contribute to the outcome measure of interest.

The one exception was the study with dyslexic children which focused on rhythm and timing skills (Overy, 2003). It had previously been shown that dyslexic children have deficits in timing tasks (e.g., Goswami et al., 2002), so it was logical to target the training accordingly.

An ideal training programme would retain the varied, engaging, motivating nature of music-making, while minimising redundancy associated with irrelevant skills. The approach taken in the current research is to first identify specific musical skills which contribute to speech perception in noise, so that an efficient, targeted training programme can be devised.

With the OPERA hypothesis in mind, a targeted musical training programme for speech perception in noise should focus on processes which are common to both music and speech. Auditory working memory is certainly one such process. However, if working memory does mediate the musician enhancement for speech perception in noise (Kraus et al., 2012), then this could be a consequence of the complex, cognitively demanding nature of musical training rather than a benefit afforded specifically by music.

Instead, the approach taken in this research is to focus on key aspects of music perception and consider how each of these might be useful for speech perception in noise.

1.8.1 Pitch and melody

As summarised in Section 1.6, spectral resolution and selective attention to frequency over time can both aid speech perception in background noise. Furthermore, frequency discrimination is enhanced in musicians and is also associated with speech perception thresholds in babble noise (Parbery-Clark et al., 2009).

In musical terms, frequency relates to pitch, and changes in pitch over time create melodies. Pitch contours are also an important aspect of speech, and artificially manipulated contours result in impaired perception of speech in background noise (Miller et al., 2010). Musicians have enhanced perception of pitch contours in both music and speech (Schön et al., 2004), suggesting that melody perception could be a potential candidate skill for targeted training.

1.8.2 Rhythm and beat

Music consists of temporal patterns – rhythms – based around an isochronous (equally spaced in time) beat. The rhythmic structure of speech consists of patterns of alternating stressed and unstressed syllables – meter. While speech meter does not necessarily contain strict isochrony, listeners can perceive and entrain to regularity in speech (Lidji et al., 2011; Schmidt-Kassow and Kotz, 2009) as they do with music.

There is also evidence that instrumental music reflects the spoken prosodic rhythms of the language of the composer (Patel and Daniele, 2000), suggesting a link between rhythm in speech and in music.

Disruptions in temporal information result in impaired speech perception (Drullman et al., 1994a,b; Ghitza and Greenberg, 2009), confirming the importance of rhythm in speech. Musicians have enhanced rhythm discrimination and this is also associated with speech perception in noise (Slater and Kraus, 2015).

There is also evidence for impaired rhythm and beat processing in groups of children who often have difficulties with speech perception in noise. For example, children with specific language impairments had difficulty tapping along to a beat (Corriveau and Goswami, 2009), children with auditory processing disorder were impaired in a rhythm task (Olakunbi et al., 2010), and dyslexic children had deficits in beat perception (Muneaux et al., 2004).

Together, these findings suggest that rhythm and beat perception – along with melody – should be considered as candidate skills for a musical training programme for speech perception in noise.

1.9 Research questions and outline of thesis

The ultimate goal of this research is to design and evaluate a short-term musical training programme for improving speech perception in background noise.

As discussed above, an efficient training programme will target specific musical skills which might contribute to speech perception in noise. This approach should reduce the redundancy associated with a comprehensive musical programme while maintaining the enjoyable nature of music-making which promotes it as a promising alternative to speech-based auditory training.

Figure 3.5 illustrates the general approach taken in this thesis. The aim is to elucidate how musical training might lead to enhancements in speech perception in noise, in order to inform the design of the training programme to be evaluated.

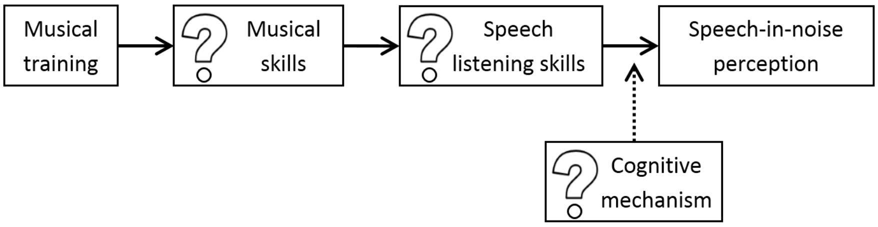


Figure 1.6: Flowchart illustrating the research questions investigated in this thesis

This approach is divided into three research questions, which will be investigated in turn:

> Question 1: Are there specific musical skills which are associated with speech perception in noise?
>
> Question 2: How might these skills contribute to speech perception in noise?

> Question 3: Can short-term training in these musical skills improve speech perception in noise?

Before embarking on an investigation of musical skills and speech perception in noise, it is crucial to select appropriate measures for each skill to be tested. Chapter 2 will outline the general methods and tests to be used in this research, and discuss the reasons for choosing these.

Chapter 3 will focus on identifying specific musical skills which could be targeted for training. The aim is to find measurable skills which are correlated both with amount of musical experience and with speech perception in noise. The sample will be drawn from the general population, thereby avoiding the pitfalls associated with defining 'musician' and 'non-musician' groups, as discussed in Section 1.7.1.1.

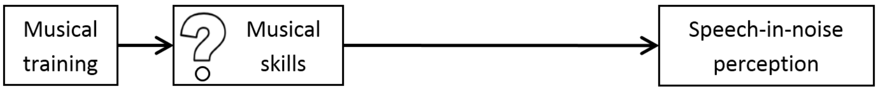
Possible mechanisms for how the identified musical skills aid speech perception in noise will be investigated in Chapters 4 and 5. The developmental aspect of such mechanisms will also be considered in a study comparing young children and adults.

Chapter 6 will discuss the design of a musical training programme based on findings from the previous chapters. The impact of the musical training programme on speech perception in noise will be evaluated for a group of older adults.

Finally, Chapter 7 will summarise and discuss the main findings of this thesis, consider limitations of the studies, and suggest directions for future research.

CHAPTER 2

General methods



The first goal of the current research is to identify musical skills which might underlie the reported link between musical training and speech perception in noise. To do this, it is first necessary to identify suitable tests for assessing speech-in-noise perception, musical experience, and musical skills. This chapter describes the requirements for each of these measures and the reasons for choosing the tests to be used in this thesis. Psychophysical methods of presenting stimuli and estimating perceptual thresholds are also introduced as these are used in Chapters 4 and 5.

2.1 Quantifying musical experience

In order to investigate the association between musical training and speech-in-noise perception in the general population, it is necessary to have an appropriate quantifiable measure of musical experience.

2.1.1 Measuring musical training

In studies which compare musicians and non-musicians, the musician group are usually defined by criteria such as duration of formal training, age at onset of training, and amount of time spent practising their instrument (e.g., Parbery-Clark et al., 2009; Zendel and Alain, 2012). These variables are often then used as proxy measures for musical training when investigating a possible dose response on some other variable (e.g., Parbery-Clark et al., 2009).

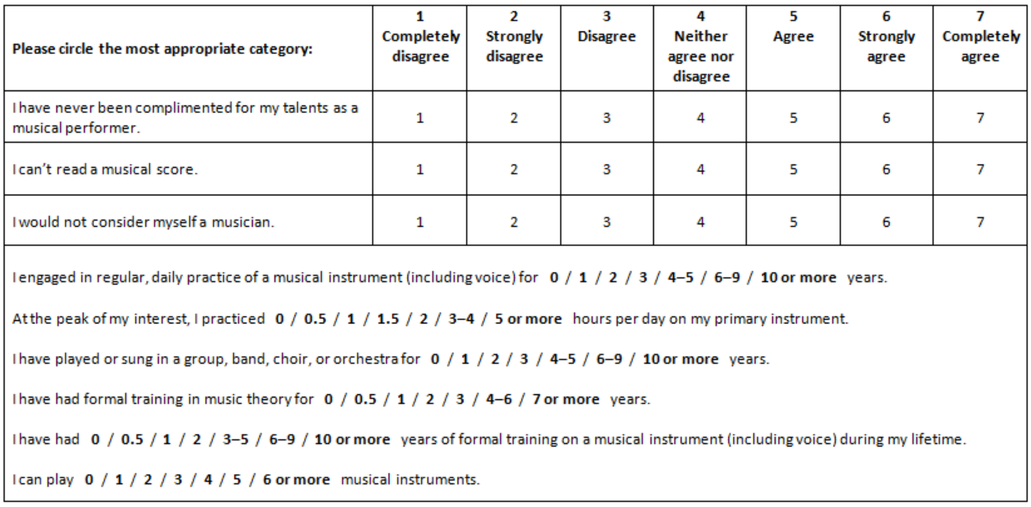
Non-musicians are usually those who do not meet the musician criteria and report having no (or little) formal training. This leaves open the possibility of having ‘musical non-musicians’, i.e., people who have aptitude or skill in music but have never pursued formal musical training (as discussed in Section 1.7.1.1). There are many types of musical experience that would not be counted as formal training but nevertheless are likely to improve musical skills.

Since one of the aims of this research is to investigate musical skills in the general population, it would be useful to have a measure of musical experience which is not limited to formal training, and would therefore provide informative (non-zero) scores for musical non-musicians.

One such measure, which has been designed specifically to quantify facets of musical sophistication in the general population, is the Goldsmiths’ Musical Sophistication Index (Müllensiefen et al., 2011). The index contains several subtests, one of which focuses on musical training, as described below.

2.1.1.1 Goldsmiths’ Musical Sophistication Index

The training subscale of the Goldsmiths’ Musical Sophistication Index (Müllensiefen et al., 2011) consists of 9 items, encompassing questions on both formal instrument training and informal musical experience. Figure 2.1 shows the training subscale in the form that it was presented to participants in the current research.



Please circle the most appropriate category:	**1** **Completely disagree**	**2** **Strongly disagree**	**3** **Disagree**	**4** **Neither agree nor disagree**	**5** **Agree**	**6** **Strongly agree**	**7** **Completely agree**
I have never been complimented for my talents as a musical performer.	1	2	3	4	5	6	7
I can’t read a musical score.	1	2	3	4	5	6	7
I would not consider myself a musician.	1	2	3	4	5	6	7

I engaged in regular, daily practice of a musical instrument (including voice) for **0 / 1 / 2 / 3 / 4–5 / 6–9 / 10 or more** years.

At the peak of my interest, I practiced **0 / 0.5 / 1 / 1.5 / 2 / 3–4 / 5 or more** hours per day on my primary instrument.

I have played or sung in a group, band, choir, or orchestra for **0 / 1 / 2 / 3 / 4–5 / 6–9 / 10 or more** years.

I have had formal training in music theory for **0 / 0.5 / 1 / 2 / 3 / 4–6 / 7 or more** years.

I have had **0 / 0.5 / 1 / 2 / 3–5 / 6–9 / 10 or more** years of formal training on a musical instrument (including voice) during my lifetime.

I can play **0 / 1 / 2 / 3 / 4 / 5 / 6 or more** musical instruments.

Figure 2.1: The nine questions of the training subscale of the Goldsmiths’ Musical Sophistication Index (Müllensiefen et al., 2011); each item is scored from 1 to 7 (the first three items are scored on a reversed scale as they are negative statements)

2.2 Assessing musical skills

As outlined in Section 1.9, the first aim of this thesis is to investigate whether specific musical skills are related to speech perception in background noise within a sample of people with a range of musical experience. The three aspects of musicality that were identified as potential predictors are melody, rhythm and beat perception (see Section 1.8).

Tests for each of these three skills are required, which are:

> *independent* – separate scores are needed for the three musical skills
>
> *suitable for use with the general population* – tests must not require any prior musical knowledge to understand the instructions or perform the tasks
>
> *auditory perception tasks* – tests must not include musical production tasks which would require expertise, nor tasks which are reliant on auditory-motor synchronisation as this could confound results
>
> *sensitive to individual differences* – a wide range of scores is needed in order to investigate relationships with other variables.

2.2.1 Melody and rhythm

There are several commonly used test batteries for musical skills, many of which have been developed for specific populations. For example, the Montreal Battery of Evaluation of Amusia (MBEA; Peretz and Hyde, 2003) uses a same/different paradigm to assess five separate melodic and rhythmic skills. However, as these tests were designed for use with people who have impaired musical abilities, there would be a ceiling effect with trained musicians. Conversely, an imitation test, which requires some level of musical performance to reproduce a heard rhythm or melody, might have a floor effect when used with non-musicians.

A popular measure of musical aptitude is Gordon's Advanced Measures of Musical Audiation (AMMA; GIA Publications, Inc., Chicago, IL, USA). This test assesses memory for melodic and rhythmic patterns using a same/different paradigm. Participants hear two musical phrases and must judge whether the second is the same as the first or differs in either rhythm or melody. One issue with this test is that the rhythm violations occur within a melodic context. The two scores are not entirely independent, as they are susceptible to attention effects, e.g., a preference for attending to melody over rhythm or vice versa. For this reason, the AMMA is not well-suited for the intended purpose.

2.2.1.1 Musical Ear Test

The Musical Ear Test (Wallentin et al., 2010) also presents pairs of musical phrases and asks the listener to judge whether they are the same or different, and it also contains subtests for melody and rhythm. The melodic phrases are made up of tones of sampled piano sounds and the rhythmic phrases use beats played on a wood block. This means that, unlike in the AMMA where the rhythm deviations occur in melodic phrases, the rhythm subtest of the Musical Ear Test assesses rhythm independently of melodic context.

Each subtest of the Musical Ear Test consists of 52 trials: 26 'same' trials and 26 'different' trials. The different trials contain one pitch or rhythm change, and the difficulty of detecting the deviations is varied by inclusion of features that alter the complexity of the phrases. The Musical Ear Test has been shown to correlate with amount of practice in a group of musicians, and can also successfully distinguish groups of professional musicians, amateurs, and non-musicians (Wallentin et al., 2010).

Another advantage of the Musical Ear Test is that the rhythm subtest has been reported to correlate with speech perception in noise within a combined group of percussionists, vocalists and non-musicians (Slater and Kraus, 2015). The Musical Ear Test will therefore be used to assess melody and rhythm skills.

2.2.2 Musical beat perception

Studies of beat skills often focus on the ability to tap along to a regular beat (e.g., Slater et al., 2013; Tierney and Kraus, 2013b). While this is an important skill in playing music, it relies on auditory-motor synchronisation and would therefore be influenced by an impairment in motor skills. It is also common for the tapping task to be synchronised to a metronome rather than to actual music (e.g., Slater et al., 2013; Tierney and Kraus, 2013b). A different approach is needed to assess musical beat perception independently of motor skills.

2.2.2.1 Beat Alignment Test

The Beat Alignment Test (Iversen and Patel, 2008) contains a perception-only subtest which does not rely on motor skills – in fact, participants are instructed not to tap or move along to the music. The test uses 12 musical excerpts (mean length 15.9 seconds ± 3.1 s) from three different genres (4 each of jazz, rock, and pop orchestral). A regular sequence of beeps (1 kHz pure tones, 100 ms duration) starts after about 5 seconds of music, and participants are required to judge whether the beeps are on or off the beat of the music.

The off-beat beeps are adjusted either in tempo (10% too fast or too slow) or in phase (30% ahead of or after the beat). The saliency of the beat, and therefore the difficulty of the task, varies considerably among the 12 excerpts, making the test suitable for examining individual differences in beat perception.

2.3 Testing speech-in-noise perception

The choice of a speech-in-noise test is not trivial. There are several factors that affect a test's suitability for a given purpose, such as the complexity of the sentence material, the acoustic properties of the noise masker, and the test procedure. It is therefore critical to consider the research questions and the target population when specifying the requirements for a speech-in-noise test.

As discussed in Chapter 1, the ultimate goal of this research is to evaluate a musical training programme in terms of potential benefit for speech perception in noise. In order to compare pre- and post-training performance, the speech-in-noise test will need to be performed multiple times by each participant. The first requirement of the speech-in-noise test is therefore that it should be repeatable, without participants being able to memorise the sentence material.

The test must also be sensitive to potentially small improvements due to training, and must be reliable so that any improvement can be attributed to training and not to test-retest differences. Sufficient sensitivity to individual differences is also crucial for the first aim of the research which is to examine associations between musical skills and speech-in-noise perception in the general population. If there is little variation in speech reception thresholds, then it will be difficult to identify any significant associations.

In order to investigate if musical skills are associated with different masker conditions, it will be necessary to compare steady and modulated maskers using the same sentence material. This will also allow for the modulation masking release to be calculated, and this could provide another potential variable of interest (see Section 1.4.2).

With multiple conditions to test, the time needed for each measure should be minimised. The most efficient way to obtain a threshold is to use an adaptive procedure, wherein the signal-to-noise ratio is altered on each trial based on the previous answer. If a correct answer is given, the next trial will be harder, and vice versa, until the procedure closes in on the threshold estimate.

Two variables which are not of interest in the current research are spatial separation and linguistic context. With the possible exception of musicians within an orchestra, musical training does not involve particular focus on using spatial cues. Similarly, there is no reason to expect that musical training would help with the accumulation of the linguistic knowledge which is necessary for using contextual cues. The first aim of the thesis is to identify musical skills which might explain individual variance in speech perception in noise. Since spatial separation and/or linguistic context would introduce variance which is not expected to be linked to musical abilities, this would be an unnecessary confound. For this reason, targets and maskers will always be colocated and sentence material will not contain semantic cues.

In summary, the ideal speech-in-noise test would be:

> *Repeatable* – sentences should not be semantically predictable nor easily learned through repetition of the test
>
> *Flexible* – able to be used with different noise maskers for comparison of conditions
>
> *Efficient* – an adaptive procedure with multiple scoring opportunities per sentence will minimise testing time
>
> *Sensitive* – capable of identifying small differences between individuals and between pre- and post-training performance
>
> *Reliable* – able to provide stable measures of an individual's performance with minimal test-retest differences

2.3.1 Choosing a sentence test

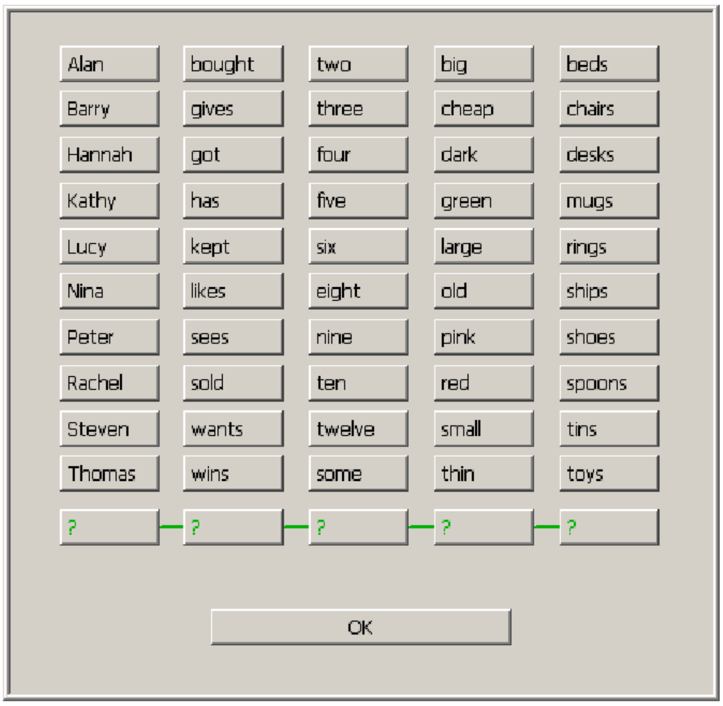
Many commonly used speech-in-noise tests (including HINT, QuickSIN and SPIN, which were discussed in Chapter 1) are designed as open sentence tests. This means that, as far as the listener is concerned, there are no restrictions on which words could occur. However, since each sentence is unique, the number of sentence lists in the corpus is limited. Repeated exposure to these lists might allow listeners to learn the sentence material, and the test would therefore become easier over time.

Closed sentence tests, on the other hand, employ a limited number of possible words for each target position, but these words can be combined to form a large number of possible sentences. This means that memorisation of the exact sentences is not possible, though some improvement is observed during an initial familiarisation phase. Sentences have the same syntactic structure and do make sense, but there is no semantic context to aid prediction of target words. Listeners can, however, make educated guesses about partially heard words since they are choosing from a finite list of options.

One example of a closed sentence test is the Coordinate Response Measure (CRM), which was introduced in Chapter 1. In this test, there are two target words in each sentence (a colour and a number), with a choice of four colours and eight numbers, giving a total of 32 possible combinations. An answer is usually deemed to be correct if both targets are identified (Allen et al., 2008; Brungart, 2001; Brungart and Simpson, 2007). Performance is often measured in terms of percent correct (Brungart, 2001; Johnsrude et al., 2013) although speech reception thresholds can also be estimated (Allen et al., 2008).

The CRM meets the criterion of repeatability, and its simple stimuli would be particularly suitable for use with children. However, the small number of possible target words (e.g., only four colours) would make it relatively easy for listeners to guess based on partial information, especially as the target words (red, white, blue, green) do not share common phonemes.

There is another closed sentence test which offers a greater number of possible target words, five scoring opportunities for each sentence, and a quick procedure for estimating the speech reception threshold: the Matrix Sentence Test.



Alan	bought	two	big	beds
Barry	gives	three	cheap	chairs
Hannah	got	four	dark	desks
Kathy	has	five	green	mugs
Lucy	kept	six	large	rings
Nina	likes	eight	old	ships
Peter	sees	nine	pink	shoes
Rachel	sold	ten	red	spoons
Steven	wants	twelve	small	tins
Thomas	wins	some	thin	toys

Figure 2.2: Screenshot of the response screen showing the matrix of possible words that make up the sentences in the Matrix Sentence Test; each sentence consists of one word from each column, for example: 'Hannah likes six pink mugs'

2.3.1.1 *Matrix Sentence Test*

Originally developed in Swedish by Hagerman (1982), and later adapted and refined for German (Kollmeier and Wesselkamp, 1997), there are now matrix sentence tests available in several languages, including a UK version which is described here (HörTech gGmbH, Oldenburg, Germany).

In this test, each target sentence has the same 5-word structure: name, verb, number, adjective, noun. The sentences are drawn from a matrix with 10 choices for each word (see Figure 2.2). The sentences make syntactic and semantic sense, but are not predictable as there are no contextual clues which might make the later words easier to guess. This means that for each sentence, there are 5 independent scoring opportunities, and an efficient adaptive procedure can be used to find a reliable threshold from a test list of 20 sentences (Brand and Kollmeier, 2002). All sentences are spoken by the same female talker, and they are all equally intelligible (Hewitt, 2008).

The sentences are not likely to be remembered, since there are 100,000 possible combinations of the base words. However, since there is a limited number of possible words, some learning does occur during the first few lists as participants become familiar with the test materials

(Hagerman, 1982; Wagener and Brand, 2005). Performance stabilises more quickly when participants are shown the matrix of possible words after each sentence presentation as opposed to recalling sentences without this information (Hewitt, 2008). After the initial familiarisation process, the test can be used repeatedly with the same subjects without any further learning effects (Wagener and Brand, 2005).

Another point in favour of the matrix test is that a similar sentence corpus was used by Swaminathan et al. (2015) in their study of musicians and non-musicians. A musician advantage was observed for perception of this kind of sentence material when it was colocated with a reversed speech (unintelligible, amplitude-modulated) masker.

Jansen et al. (2012) compared the French version of the matrix test to an everyday sentence test (similar to HINT) and a digit triplets test (usually used to screen for hearing loss). They found that all three tests correlated with each other, and that the matrix test was better able to distinguish between individuals than the other two tests.

The Matrix Sentence Test appears to be a good choice to meet the criteria of repeatability and sensitivity, although sensitivity also depends on the type of noise maskers used, as discussed in the next section.

2.3.2 Selecting noise maskers

The choice of masker can have substantial effects on the properties of a speech-in-noise test. For example, amplitude-modulated maskers provide better differentiation between listeners (George et al., 2007; Wagener and Brand, 2005) but may also make the test less reliable (Wagener and Brand, 2005). The masker supplied with the matrix test is a steady speech-spectrum noise, matching the long-term spectrum of the sentence material (Hewitt, 2008). It is also possible to introduce additional noise signals into the software in order to compare performance in different conditions.

Wagener and Brand (2005) examined the influence of different noise maskers using the German matrix test with normal-hearing and hearing-impaired listeners. They compared the steady noise with two fluctuating noises: icra5 and icra7 (Dreschler et al., 2001). The ICRA maskers are artificial noise signals which were designed to mimic some of the spectral and temporal properties of different types of speech, but with no actual speech content (Dreschler et al., 2001). The icra5 masker simulates the modulations in speech with a single male talker; icra7 represents a babble noise of six people speaking concurrently.

Overall, Wagener and Brand (2005) recommended using fluctuating, speech-shaped noise if the goal is to differentiate between subjects. However they noted that the highly fluctuating icra5 noise has long gaps (up to 2 seconds, which is a long time in the context of a 5-word sentence) which reduced the test-retest reliability. This loss of reliability can be reduced, while retaining the improved sensitivity, by using an adapted version of icra5 in which the maximum gap length is 250 ms (Wagener, 2003).

An alternative approach, which affords greater control over the fluctuations in noise level, is to modulate the amplitude of a steady noise by applying a regular function, such as a sine wave (Gnansia et al., 2008). Manipulation of the modulation parameters (frequency and depth) has a direct effect on the amount of masking release observed (Gnansia et al., 2008). This technique has successfully been used in investigations of 'dip listening' (see Section 1.4.2).

2.3.2.1 Creation of modulated noise maskers

In order to compare the sensitivity and reliability of the matrix test with different noise conditions, two additional maskers were created. Each modulated masker was made by applying a sinusoidal amplitude-modulation to the standard speech-spectrum noise:

$$m(t) = [1 + d\text{sin}(2\pi f t)]n(t) \tag{2.1}$$

where $n(t)$ is the steady noise masker; d is the modulation depth (0.6 or 0.8); and f is the modulation frequency (8 Hz). The two modulation depths (60% and 80%) were chosen to give moderate and high amounts of masking release respectively (Gnansia et al., 2008). All noise signals were subsequently matched in overall intensity (root-mean-square level). Waveforms for all three noise maskers are shown in Figure 2.3.

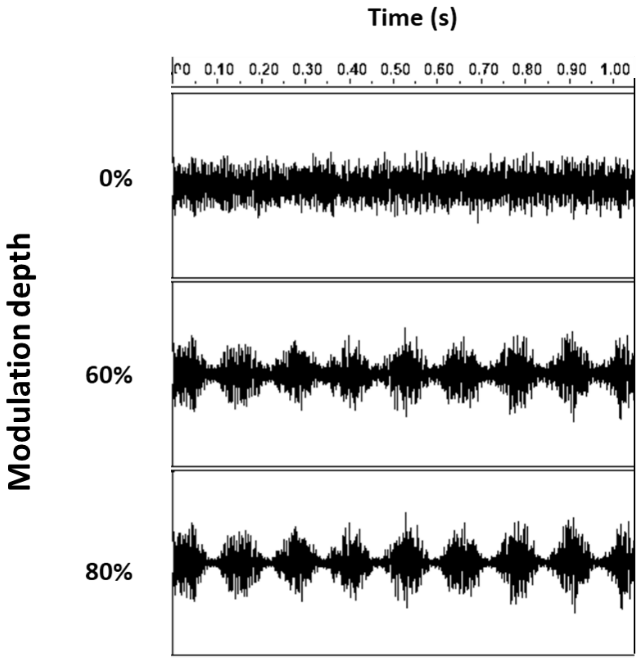


Figure 2.3: Example waveforms of the three noise maskers to be used with the matrix sentence test: steady noise (0% modulation depth) and two sinusoidally amplitude-modulated noises (modulation frequency = 8 Hz; modulation depths of 60% and 80%)

2.4 Psychophysics

Psychophysical methods attempt to quantify the relationships between external stimuli and perception. By systematically varying the stimulus in some way, and recording performance on a perceptual task, a psychometric function can be plotted. Figure 2.4 shows an example psychometric function for a speech perception in noise task. Here the stimulus is varied by way of the signal-to-noise ratio (SNR) and performance is measured in terms of the percentage of words correctly identified for a given SNR. Above a certain SNR, the task becomes very easy and all words can be identified. Similarly, below a certain SNR, the task is so difficult that performance will be at chance level. The area of interest is the slope in between these two extremes, and particularly the speech reception threshold, i.e., the SNR for which performance is equal to 50% correct.

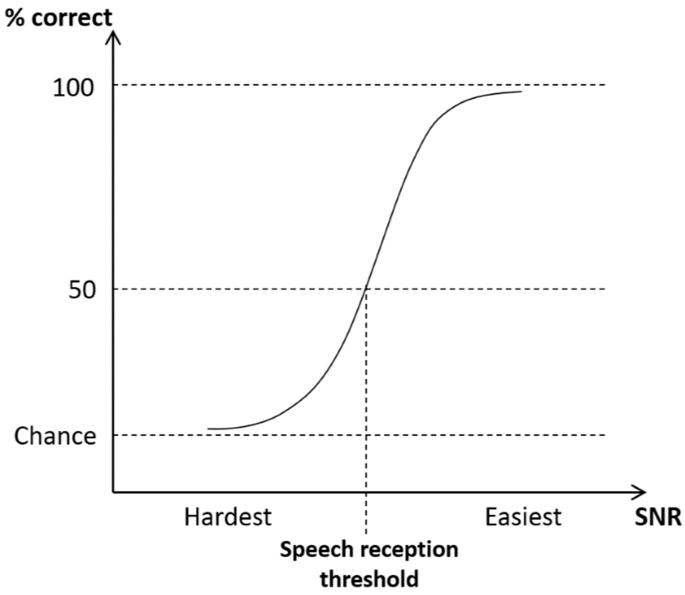


Figure 2.4: An example psychometric function for a speech perception in noise task

In order to estimate the perceptual threshold, the psychometric function must be plotted as accurately as possible. Data points at ceiling or floor do not provide much information about the shape of the psychometric function. Data need to be sampled at various points (i.e., performance measured for various SNRs) along the slope of the function in order for a curve to be fitted.

2.4.1 Adaptive staircases

An efficient way to sample the psychometric function is via an adaptive procedure such as a staircase (Levitt, 1971). An adaptive staircase does just what its name suggests: starting from a relatively easy SNR, the signal level is then stepped up or down depending on the response given. A correct response is followed by a more difficult trial, while an incorrect response is followed by an easier trial. Different staircases target different threshold levels. For example, a 3-down 1-up staircase, in which 3 correct responses are required before the level is made harder but a single incorrect response would make it easier, targets the 79% threshold (Levitt, 1971).

Using an adaptive staircase procedure means that within a few trials the observed performance will be around threshold level, and the remaining trials will provide information about the slope of the psychometric function. This is an efficient method for estimating the threshold, but it does have some disadvantages. For example, presenting the majority of targets close to threshold level can be frustrating for the participant if the staircase is targeting a fairly difficult threshold (e.g., 50%).

Another problem with adaptive staircases is their sensitivity to differences in perceptibility between targets. In an established sentence-in-noise test, such as the Matrix Sentence Test described above, a considerable amount of care is put into ensuring that every sentence in a list is matched in terms of perceptibility. If this were not the case, then the occurrence of an unusually easy target at a difficult SNR, or an unusually difficult target at an easy SNR, could result in an undue reversal of direction during the staircase which would affect the threshold estimate.

2.4.2 Method of constant stimuli

The method of constant stimuli is another procedure for sampling the psychometric function. A number of SNRs are chosen in advance and stimuli are presented several times at each level, within a randomised block of trials. Ideally, the SNRs are chosen so that at most one level is close to ceiling performance and at most one level is close to floor performance, guaranteeing that the majority of data will provide useful information about the slope of the psychometric function.

One disadvantage of the method of constant stimuli is that each threshold estimate requires a large number of trials. In such a time-consuming method, it is important to ensure that useful data is collected efficiently. If the chosen SNRs do not cover a range of performance, with sufficient data around the threshold, then time is wasted on collecting uninformative data (i.e., large numbers of trials at ceiling or floor performance).

2.4.3 Threshold estimates from fitted functions

Once the data have been collected, a psychometric function is plotted. Figure 2.5 shows two examples: one for a tone-detection task and one for a speech-in-noise task. The latter was already discussed above, and the differences to note for the tone-detection task are visible on the vertical axis: performance is measured in terms of the percentage of ‘yes’ responses; the lower limit of performance is set as the participant’s false alarm rate, i.e., the proportion of no-signal trials for which the participant reported hearing a target tone.

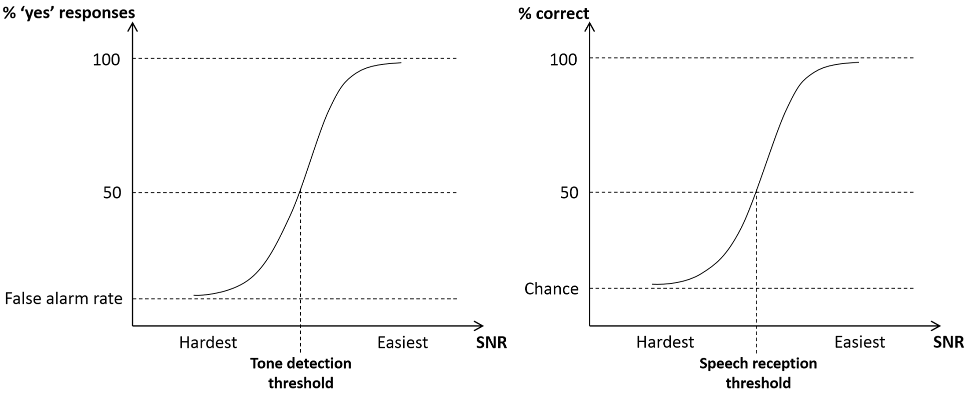


Figure 2.5: Using the method of constant stimuli to estimate thresholds: when fitting psychometric functions, the lower limit of the function is defined to be the false alarm rate for a tone-detection task (left) and chance-level performance in a speech-perception task (right)

In order to estimate the threshold, a psychometric function must be fitted to the data. For the data in Chapters 4 and 5, functions were fitted using the Palamedes toolbox for Matlab (Kingdom and Prins, 2009). There are several possible forms of psychometric function, but in most cases a logistic curve provided a good fit for the data (see Equation 2.2). Curves were fitted for each condition for each participant in order to obtain estimates for the threshold (α) and slope parameter (β).

$$f(x;\alpha,\beta)=\frac{1}{1+\exp(-\beta(x-\alpha))} \tag{2.2}$$

For each condition, the fitted slope parameter, β, was converted to give a meaningful value for the slope of the function. This was calculated as $(f(\alpha+1)-f(\alpha))\times 100$, and indicates the percentage change in performance per dB change in SNR at threshold (α).

This is a useful metric for comparing conditions, but it should be noted that this figure only applies to signal-to-noise ratios in the region of the speech reception threshold (i.e., the SNR which results in 50% correct performance). As shown in Figure 2.4, this is the steepest part of the psychometric function. Further away from the threshold – i.e., at very challenging or very easy signal-to-noise ratios where the slope is shallower – the same change in SNR would equate to little change in task performance. It is therefore difficult to interpret the results in terms of real world benefit, since this will vary for different listening environments.

2.4.4 Quantifying rhythmic priming effects

For the rhythmic priming experiments in Chapter 4, a quantifiable measure was needed for the magnitude of the rhythmic priming effect. As discussed in Section 1.5.1.2, dynamic attending theory suggests that a regular rhythm leads to enhanced processing for on-beat targets compared to temporally displaced targets. Specifically, the oscillatory nature of such anticipatory attention (see Figure 1.3) results in a quadratic performance profile centred around the on-beat target position (Jones et al., 2002).

Therefore, for the rhythmic priming experiments, quadratic curves were fitted to the data (see Equation 2.3).

$$f(x) = ax^2 + bx + c \tag{2.3}$$

The strength of the rhythmic priming effect was defined to be the coefficient (a) of x^2 in the fitted function. The greater this coefficient, the steeper the curve, and the greater the priming effect (see Figure 2.6).

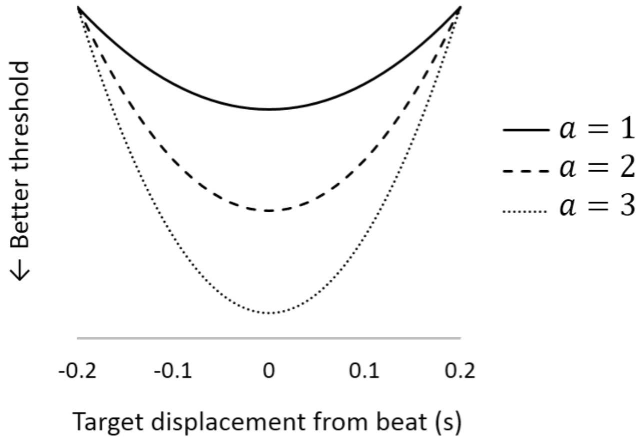
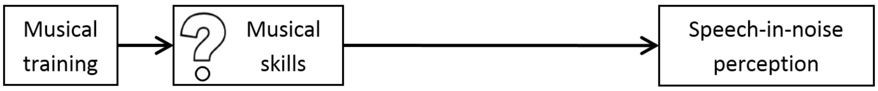


Figure 2.6: Illustration of the quadratic coefficient as a measure of priming effect: the greater the value of a, the greater the benefit for on-beat targets compared to temporally displaced targets

CHAPTER 3

Investigating musical skills for speech perception in noise



This chapter presents results of a correlational study which investigated the relationships between musical experience, musical skills, and speech perception in noise for a sample of participants with a range of musical backgrounds. The main aim of this study was to identify specific musical skills which could be targeted in a musical intervention for improving speech perception in background noise.

3.1 Introduction

The ultimate goal of this thesis is to design and evaluate a short-term musical training programme for improving speech perception in background noise. As discussed in Section 1.9, the first step towards this goal is to identify specific musical skills which could be targeted for training. In addition, a reliable outcome measure for speech-in-noise perception is required which will be sensitive to training-related improvements. Experiment 1 was designed to address these aims.

3.2 Experiment 1

3.2.1 Aims

The aims of Experiment 1 were threefold, and each is discussed in turn below.

3.2.1.1 Assess suitability of matrix sentence test with different noise maskers

An ideal speech-in-noise test will be both sensitive and reliable, and these qualities can be assessed in terms of inter- and intra-subject variability:

> *Inter-subject variability* – this is a measure of the sensitivity of the test and should be maximised. Greater variation between subjects means that the test is more sensitive to individual differences. This also facilitates correlational analyses as relationships may not be apparent if there is a very narrow range of observed values.
>
> *Intra-subject variability* – this is a measure of the reliability of the test and should be minimised. If repeated scores from a single participant do not agree with each other, then the test is not reliable.

According to Wagener and Brand (2005), the inter-subject variability should be at least twice the intra-subject variability in order for the test to significantly discriminate between participants.

Amplitude-modulations in a masking noise allow listeners to benefit from temporary increases in signal-to-noise ratio (SNR) and this usually results in an improved speech reception threshold (SRT) (Wagener and Brand, 2005). Listeners vary in their ability to take advantage of these dips in noise level, so a greater range of SRTs is commonly observed for modulated maskers compared to steady noise maskers (George et al., 2007; Wagener and Brand, 2005). Use of a modulated masker therefore improves a test's ability to differentiate between subjects, but this increased sensitivity comes at a cost in terms of test-retest reliability (Wagener and Brand, 2005).

In order to identify suitable measures for speech-in-noise perception for use in future studies, three maskers were included in the current study: one steady noise and two modulated noises. The same sentence material was used with each masker, which allowed for direct comparisons of the sensitivity and reliability of the test in each condition. The intention behind including two modulated maskers was to choose the one which provided the best ratio of inter- to intra-subject variability, i.e., the best ability to reliably discriminate between subjects.

Although modulated noise maskers were predicted to provide better differentiation between individuals, the steady masker was also included in order to calculate the modulation masking release (i.e., the improvement for modulated versus steady noise). If a skill is associated with masking release, then it is likely to contribute to dip listening. As discussed in Section 1.4.2, such skills might include working memory and temporal resolution. On the other hand, if a skill is associated with speech perception in steady noise, then it likely contributes to the separation of the target speech from the background noise, via either auditory scene analysis (see Section 1.2.2) or orienting of attention (see Section 1.3).

3.2.1.2 Investigate the link between musical experience and speech perception in noise

The evidence for a link between musical training and speech-in-noise perception has so far come from studies comparing highly trained musicians with non-musicians (Parbery-Clark et al., 2009; Swaminathan et al., 2015; Zendel and Alain, 2012). Given the intended short-term nature of a musical intervention, it would not be sufficient to identify associations in a population of highly trained musicians who have spent years honing their skills. If a relationship exists only for lifelong musicians, then it is unlikely that short-term musical training would be beneficial for improving speech perception in noise. This study did not use any musical criteria to recruit participants, in the hope that associations between musical experience, musical skills and speech-in-noise perception could be examined for a general population sample with a range of musical backgrounds.

3.2.1.3 Examine associations between musical skills and speech perception in noise

In order to inform the design of a targeted training programme, this study aimed to find specific musical skills which are correlated with both musical experience (indicating that they might be improved by training) and speech-in-noise perception.

In Section 1.8, three musical skills were identified as potential candidates for training: melody, rhythm, and beat perception. Tests for each of these skills were introduced in Chapter 2. When examining relationships between these measures and speech reception thresholds, it is necessary to consider the nature of each test and whether other factors might mediate any observed association. In particular, it is important to control for variables which might influence scores on the musical tests despite not being directly related to the musical skill of interest. Partial correlations will therefore be carried out to examine the associations between musical skills and speech perception in noise while controlling for the variables discussed below.

For the melody and rhythm tests, performance is certainly reliant on working memory as the phrases need to be stored while making same/different judgements. Working memory has been shown to be enhanced in musicians (e.g., Chan et al., 1998; Jakobson et al., 2008), associated with speech-in-noise perception (Akeroyd, 2008), and has been suggested to mediate the musician enhancement for speech-in-noise perception (Parbery-Clark et al., 2009). Therefore, to assess any specific contribution of melody or rhythm skills to speech reception thresholds, working memory needs to be measured so that it can be controlled for in the analysis.

The design of the beat perception test involves pure-tone 'beeps' superimposed over music. If a listener has very poor frequency discrimination, they may not be able to separate the beeps from the music and this would impair performance on the task. In this case, their score might not be an accurate reflection of beat perception per se. Frequency discrimination is enhanced in musicians and is associated with speech perception in some masking noises (Parbery-Clark et al., 2009). The test also requires the perception of musical beat to be held in memory while making a judgement about the superimposed beeps. It is therefore important to control for frequency discrimination and working memory when examining associations with beat perception.

There are other psychoacoustic factors which would influence performance on the musical skill tests, but these are not considered confounding variables as they are an integral part of the skill being measured. For example, frequency discrimination is likely associated with performance on the melody test since poor frequency discrimination would impair the ability to judge changes in the melodic sequences. Similarly, temporal resolution is likely associated with the ability to judge whether or not a beep occurred on the beat, but this is an essential part of beat perception and so was not included as a possible confound in this study.

3.2.2 Methods

3.2.2.1 Participants

Twenty-four native English speakers (10 male; age range 19–40, mean age 25.9, standard deviation 6.1 years) were recruited via posters from the University of Nottingham student population and the general public, and they received an inconvenience allowance for taking part. All participants had normal hearing, defined as pure-tone audiometric thresholds of $\leq$20 dB HL across octave frequencies from 250 Hz to 8 kHz. Participants were also screened for normal non-verbal IQ using the Matrix Reasoning subset from the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999).

3.2.2.2 Procedure

Testing took place in a sound-attenuating booth, and auditory stimuli were presented diotically through Sennheiser HD-25 headphones. The order of the test battery is shown in Table 3.1. The same order was used for all participants, with the exception of the order of the three noise masker conditions which was counterbalanced across participants. The protocol was designed to aid attention by varying the tasks, e.g., by alternating between speech and music tasks, and participants were permitted to take breaks when needed. Details of the individual test procedures are given below.

Table 3.1: The test battery used for Experiment 1

	Task	**Approximate duration (minutes)**
1	Auditory working memory	5
2	Frequency discrimination	5
3	Speech in noise: Masker 1	20
4	Musical skill: Melody	10
5	Speech in noise: Masker 2	20
	Break	15
6	Musical skill: Rhythm	10
7	Speech in noise: Masker 3	20
8	Musical skill: Beat perception	15
		Total = 120

Auditory working memory

The digit span from the Wechsler Adult Intelligence Scale (Wechsler, 2008) was used as a measure of auditory working memory. Both forward and backward subtests were administered to give an overall total. For the forward subtest, the experimenter read aloud strings of digits (at a rate of one digit per second), starting with 2 digits and working up to a maximum of 9, with two trials for each string length. Participants were required to repeat all of the digits in the correct order to score a point for that trial. The test was stopped if a participant failed on both trials at a given sequence length. The procedure was then repeated for the backward test in which participants had to repeat the digits in reverse order (up to a maximum length of 8 digits).

Pure-tone frequency discrimination

Frequency discrimination thresholds were obtained using a three-interval three-alternative forced-choice procedure, with stimuli created and presented using Matlab v2008a (The MathWorks, Natick, MA). Each trial consisted of three tones of 100 ms duration (including 15 ms cosine on/off ramps) with an interstimulus interval of 300 ms. Two of the tones were identical (standard frequency, $f = 1$ kHz) while the target tone had a frequency of $f + \Delta f$ where Δf was determined adaptively as a percentage of f. The order of the three tones was randomised on each trial, and the participants were instructed to press the button that corresponded to the tone that was different from the other two. There was no time limit for the response, and visual feedback was given after each trial. An adaptive staircase procedure was used to target the 79.4% correct threshold. The starting value of Δf was 50%, and this was divided by 2 after each correct response until the first reversal, after which a 3-down 1-up staircase was implemented with a factor of $\sqrt{2}$. Participants completed five practice trials followed by two tracks (of 50 trials each); the two thresholds were averaged to obtain the final score.

Speech-in-noise perception

The UK Matrix Sentence Test (HörTech gGmbH, Oldenburg, Germany) was used to determine the speech reception threshold (SRT; the signal-to-noise ratio (SNR) that equated to 50% intelligibility). In this test, sentences take the form name–verb–numeral–adjective–noun and are formed from a closed matrix with 10 possible choices for each word (see Section 2.3.1.1 and Figure 2.2).

Three maskers were used: an unmodulated speech-spectrum noise (supplied with the test; also referred to as steady or 0% modulation depth noise) and two sinusoidally amplitude-modulated versions of the original noise (modulation frequency of 8 Hz for both; modulation depths of 60% and 80%). The modulation parameters were chosen as they had previously been shown to give moderate and high amounts of masking release respectively (Gnansia et al., 2008). See Section 2.3.2.1 and Figure 2.3 for further details of the stimuli. All noise signals were matched in overall intensity (root-mean-square level).

Each test list consisted of 20 sentences. On each trial, the noise signal started from a random point at a level of 65 dB. The starting SNR was 10 dB, i.e., the speech started at a level of 75 dB, and was adaptively varied to target the SRT (50% correct). After each sentence, the matrix of possible words appeared on screen and participants used a touch screen or mouse to select the words they had heard. There was no time limit for responses and no feedback was given.

For each masker, participants completed a block of four test lists: one practice run which was not included in the analysis, and three further lists which were used to obtain an average SRT. The order of these three blocks was counterbalanced across participants.

Musical experience

The training subscale of the Goldsmiths' Musical Sophistication Index (Müllensiefen et al., 2011) was used as a measure of musical experience. The subscale consists of 9 questions which encompass both formal instrument training and informal musical experience (see Figure 2.1).

Musical skills: Melody and rhythm

The Musical Ear Test (Wallentin et al., 2010) was used to measure memory and rhythm skills in separate subtests. The melodic phrases are made up of 3–8 tones of sampled piano sounds while the rhythmic phrases consist of 4–11 unpitched sounds from a wood block. Each subtest has 52 trials: 26 'same' trials and 26 'different' trials. The 'different' trials contain one deviation, in pitch or rhythm for the subtests respectively. Participants listened to the instructions and two example pairs (one same, one different) at the beginning of each subtest, and then recorded their responses on an answer sheet. The order of trials was randomised, and no feedback was given during the test.

Musical skills: Beat perception

The auditory-only subsection of the Beat Alignment Test (Iversen and Patel, 2008) was used to measure musical beat perception. The test uses 12 musical excerpts (mean length 15.9 ± 3.1 seconds) from three different genres (4 each of jazz, rock, and pop orchestral). A train of beeps (1 kHz pure tones, 100 ms duration) starts after about 5 seconds of music, and is either on or off the beat. The off-beat beeps are adjusted either in tempo (10% too fast or too slow) or in phase (30% ahead of or behind the beat). The test comprises 36 trials: 12 on the beat and 6 each of the four off-beat conditions. For each excerpt, one on-beat, one tempo-adjusted and one phase-adjusted trial is included. Before the test, participants heard a demonstration of the beeps on their own, two on-beat examples (the same excerpt with beeps at two different tempi), and two off-beat examples (one tempo-adjusted, one phase-adjusted). Participants were instructed not to move or tap along to the music, but just to listen and record on an answer sheet whether the beeps were on or off the beat.

3.2.2.3 Analysis

Comparison of noise maskers

The means and standard deviations for the speech reception thresholds (SRTs) with the three different maskers are shown in Figure 3.1. As expected, performance improved with increased modulation depth, reflecting the benefit of dip listening.

One participant was identified as having thresholds more than 2 standard deviations from the group mean. Exclusion of this participant had very little effect on the analysis comparing the masking conditions, however, and so all data were included in this analysis.

An ideal masker would provide maximal inter-individual variation, allowing for differentiation between subjects, while minimising intra-individual variation across multiple lists, ensuring test-retest reliability. According to Wagener and Brand (2005), the ratio of these two measures should have a value of at least 2 in order for the test to significantly discriminate between participants. Another measure of reliability is the intraclass correlation. This is a measure of consistency which can be applied when more than two measurements are taken, as was the case here. These statistics are given in Table 3.2.

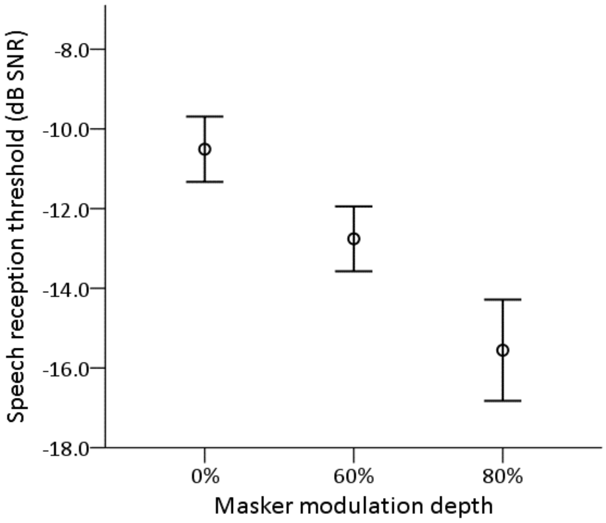


Figure 3.1: Means (and standard deviations) of the speech reception thresholds for the three different masking conditions

Table 3.2: Sensitivity and reliability statistics for the matrix sentence test with the three different noise maskers; 0% modulation depth refers to the steady noise masker (no modulation applied)

Masker modulation depth	**0%**	**60%**	**80%**
Mean threshold (dB SNR)	−10.51	−12.76	−15.55
Inter-subject standard deviation (dB)	.82	.81	1.27
Intra-subject standard deviation (dB)[a]	.27	.44	.50
Inter s.d. / intra s.d[b]	3.01	1.87	2.52
Intraclass correlation[c]	.90	.76	.85

[a] Derived from the one-way ANOVA (subject as factor): root mean square error term divided by $\sqrt{3}$

[b] This should be at least 2 in order to reliably discriminate between subjects (Wagener and Brand, 2005)

[c] Two-way mixed model consistency measure based on averaging three lists

Comparing the two modulated noises, it is clear that the 80% depth masker offered the better differentiation (higher inter-subject standard deviation) and also the better reliability (lower intra-subject standard deviation and higher intraclass correlation). The 60% modulation depth masker provided no improvement in differentiability compared to the steady masker, while also showing reduced reliability. Data from the 60% depth masker was therefore excluded from further analysis.

From this point, the two maskers used in the analysis will be referred to as ‘steady’ and ‘modulated’ (80% modulation depth), and the difference between these two thresholds will be called the ‘masking release’ (modulated SRT minus steady SRT). The intraclass correlations (see Table

3.2) for both of these maskers were very high, demonstrating that these measures are very reliable when an average of three thresholds is used.

Checking for bivariate outliers

As mentioned above, one participant was identified as a possible outlier in terms of speech reception thresholds. To investigate this potential outlier, preliminary regression analyses were run. Based on previous findings (Parbery-Clark et al., 2009), the variables of musical experience, frequency discrimination and working memory were all expected to be associated with speech perception in modulated noise. For each of these variables, a separate regression analysis was run (with a single predictor and modulated SRT as the dependent variable). In all three cases, the potential outlier had a studentized residual greater than 2, suggesting that this participant was a bivariate outlier in the analyses as well as an outlier in speech-in-noise perception. Given the small sample size and the undue influence of this single case, it was decided to exclude this participant from further analysis.

Correlation analysis

The normality assumption was checked for all variables using a combination of histograms, probability plots and Kolmogorov-Smirnov tests. The only variable which was not normally distributed was frequency discrimination, which was highly skewed. A reciprocal transformation was applied to the frequency discrimination data (i.e., new score = 1/original score) which resulted in normalised data.

Pearson correlations were performed to investigate the relationships among all the variables. Given the exploratory nature of the study, the data were not corrected for multiple comparisons, although correlations which would persist even with stringent (Bonferroni) corrections were identified. Finally, partial correlation coefficients were calculated to examine the relationships between musical skills and speech reception thresholds when controlling for frequency discrimination and working memory.

3.2.3 Results

3.2.3.1 Relationships among predictor variables

Figure 3.3 shows the relationships among the predictor variables; corresponding correlation coefficients are given in Table 3.3. All correlations are in the expected direction (i.e., better performance on one task relates to better performance on the other).

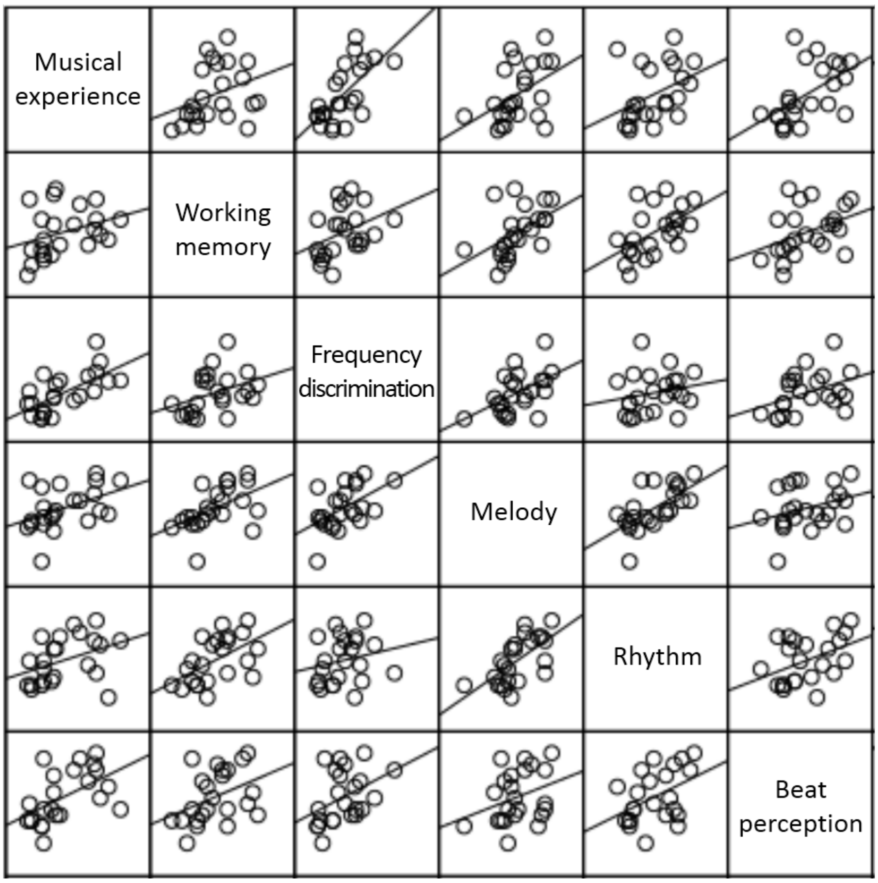


Figure 3.2: Scatter matrix showing the relationships between predictor variables

Table 3.3: Pearson correlation coefficients for the relationships between predictor variables

	Predictor variables	1	2	3	4	5	6
1	Musical experience	–	.33	.66***	.44*	.39*	.54**
2	Working memory		–	.38*	.50**	.54**	.40*
3	Frequency discrimination			–	.52**	.21	.40*
4	Melody				–	.64***	.32
5	Rhythm					–	.44*
6	Beat perception						–

*$p<.05$, **$p<.01$, ***$p<.00147$ (Bonferroni corrected alpha level for 34 comparisons); all one-tailed

Musical experience was strongly correlated with frequency discrimination which is consistent with previous findings that musicians have enhanced frequency discrimination (e.g., Micheyl et al., 2006; Parbery-Clark et al., 2009). There was no significant correlation between musical experience and working memory, which was unexpected given the reported musician advantage for auditory working memory (Chan et al., 1998; Parbery-Clark et al., 2009). However, this might have been influenced by the choice of memory test. The digit span is a fairly simple measure of working memory with a limited range of scores. This may have reduced the observed correlation in comparison to a more complex combined measure such as that used by Parbery-Clark et al. (2009) which would have given a wider range of individual variation.

All three musical skills improved with increased musical experience, as would be expected if these skills are improved through training, although the moderate correlations would not reach significane if corrected for multiple comparisons.

The melody and rhythm subtests were strongly related to each other and also to working memory as expected. The shared variance is likely due to the nature of the same/different task which is dependent on working memory. The skill-specific variance is evident in the fact that melody – but not rhythm – was related to frequency discrimination as expected.

3.2.3.2 Predictors of speech reception thresholds

The speech reception thresholds for steady and modulated noises were strongly correlated (r=.86, p<.001). This demonstrates the benefit of using the same sentence material with different maskers when investigating modulation masking release. For example, Parbery-Clark et al. (2009) found that HINT and QuickSIN were not related and had different patterns of associations with other variables, but as these tests differ in both complexity of sentences and maskers, it is not clear which is the most important factor.

Figure 3.3 shows the relationships between the six potential predictor variables and the three speech perception in noise measures. The corresponding correlation coefficients are given in Table 3.4. All trends are in the expected direction (i.e., better (higher) scores for predictor variables associated with better (lower) speech reception thresholds and greater (more negative) masking release).

Musical experience was moderately correlated with SRTs in steady and modulated noise (although these correlations would not be significant if corrected for multiple comparisons). This supports the notion that a link between musical training and speech-in-noise perception might exist in the general population, rather than being restricted to lifelong musicians.

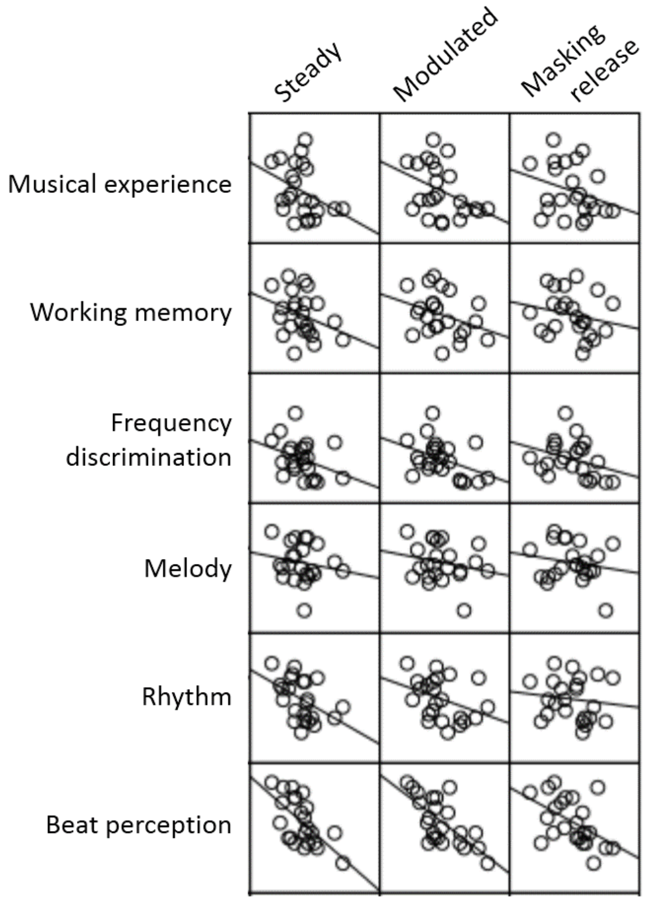


Figure 3.3: Scatter matrix showing the relationships between predictor variables and the three measures of speech perception in noise: SRT in steady noise, SRT in modulated noise, masking release (benefit for modulated versus steady noise)

Table 3.4: Pearson correlation coefficients for the relationships between predictor variables and the three speech-in-noise perception measures: steady, modulated, and masking release

Predictor variables	Steady	Modulated	Release
Musical experience	−.36*	−.40*	−.29
Working memory	−.33	−.33	−.21
Frequency discrimination	−.34	−.41*	−.33
Melody	−.18	−.22	−.18
Rhythm	−.46*	−.37*	−.13
Beat perception	−.62***	−.69***	−.50**

*$p<.05$, **$p<.01$, ***$p<.00147$ (Bonferroni corrected alpha level for 34 comparisons); all one-tailed

Musical beat perception was strongly correlated with SRTs in steady and modulated noise, and these correlations would still be significant with a stringent correction for multiple comparisons (Bonferroni). Beat perception was also strongly correlated with modulation masking release. The rhythm test was also moderately correlated with speech reception thresholds in steady and modulated noise. Together these results suggest that a training programme focusing on temporal aspects of music (i.e., beat and rhythm) could be a good candidate for improving speech-in-noise perception.

However, as discussed in Section 3.2.1.3, it is important to control for possible confounds due to test design before attributing the shared variance to a specific musical skill. Partial correlations were therefore carried out to control for working memory and frequency discrimination as planned.

Partial correlations

Table 3.5 gives the partial correlations between rhythm and beat perception and speech-in-noise measures while controlling for possible confounding variables.

Table 3.5: Partial correlation coefficients for the relationships between predictor variables and the three speech-in-noise measures, controlling for working memory (WM) and frequency discrimination (FD)

Partial correlations	Steady	Modulated	Release
Rhythm (controlling for WM)	–.36	–.23	–.02
Beat perception (controlling for WM & FD)	–.54**	–.61**	–.42*

*p<.05, **p<.01 (all one-tailed)

When controlling for working memory, the association between rhythm and speech-in-noise perception is considerably reduced, just failing to reach significance for the SRT in steady noise (p=.05). This suggests that rhythm perception – as measured by the Musical Ear Test – is not related to speech perception in noise, and the original correlation was simply due to working memory. However, the design of the same/different task means that the skill being tested is actually memory for rhythm. Perhaps an alternative task which tests rhythm perception without such working memory demands might reveal a relationship with speech perception in noise. This will be discussed further in Chapter 7.

Beat perception is strongly correlated with SRTs in steady and modulated noise, and moderately with masking release, even when controlling for working memory and frequency discrimination. Figure 3.4 shows the scatter plots for beat perception against the three speech-in-noise measures both before (left) and after (right) controlling for these two factors.

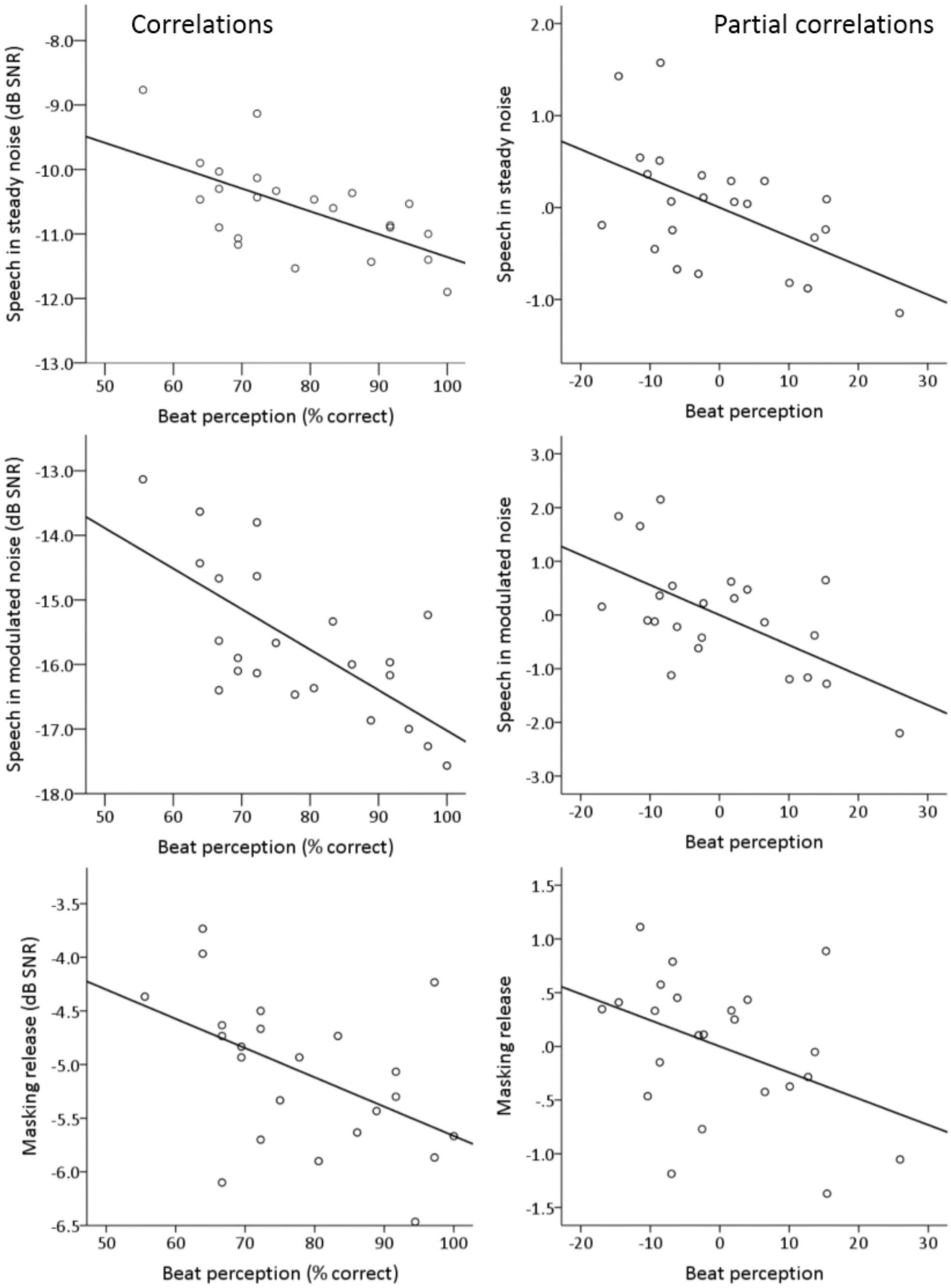


Figure 3.4: Scatter plots showing the relationships between musical beat perception and the three measures of speech perception in noise; the right-hand column shows the partial plots when controlling for working memory and frequency discrimination

The fact that beat perception was associated with the amount of masking release suggests that it is linked with the ability to listen in the dips of the noise. It is possible that the relationship is mediated by temporal resolution, as this would be important both for judging temporal alignment of the beeps in the beat test and for taking advantage of dip listening (see Section 1.4.2).

If temporal resolution were the only factor underlying the association between beat perception and speech perception in noise, then strong correlations would have been expected only for speech in modulated noise and masking release. The equally strong correlation between beat perception and speech perception in steady noise – where there are no opportunities for dip listening – suggests that there is another mechanism linking beat perception and speech perception in noise. This will be discussed further below.

3.3 Discussion

Previous research has shown that highly trained musicians have an enhanced ability to perceive speech in background noise when compared to non-musicians (Parbery-Clark et al., 2009, 2011; Swaminathan et al., 2015). Experiment 1 used a correlational design to explore the link between musical experience and speech-in-noise perception in a sample of participants with a range of musical backgrounds. The aims of the study were threefold:

1. To identify a suitable modulated masker for use with the Matrix Sentence Test which can reliably discriminate between individuals
2. To assess whether an association between musical experience and speech-in-noise perception is observable in a sample of participants with a range of musical histories
3. To identify specific musical skills which are associated with speech perception in noise

3.3.1 Evaluation of noise maskers

Three noise maskers were used with the Matrix Sentence Test: a steady speech-spectrum noise, and two sinusoidally amplitude-modulated versions of the steady noise. Comparison of the sensitivity and reliability statistics for the three conditions revealed that the masker with a modulation depth of 60% was unsatisfactory in its ability to reliably distinguish individual differences. The steady noise and the masker with a modulation depth of 80% both met the requirements for a reliable and sensitive test.

As expected, modulation of the background noise led to increased inter-individual differences even within a normally hearing young adult sample. As discussed in Section 1.4.2, modulation masking release depends on good temporal resolution and places extra demands on working memory and linguistic knowledge to reconstruct the partial signal. Since individuals vary in all of these abilities, the sensitivity of this test will likely be further increased in populations which already have greater variation for speech perception in noise. For example, for people with hearing loss, speech perception in steady noise depends mainly on their hearing acuity, whereas speech perception in modulated noise additionally depends on non-auditory cognitive and linguistic factors (as measured by the text reception threshold, see Section 1.4.1; George et al., 2007).

The use of both steady and modulated maskers with the same sentence material allows for the calculation of masking release which can be a useful measure in its own right. Future studies should therefore include both of these masking conditions. In each case, the test is reliable when a practice list is discarded and an average threshold is obtained from three repeated lists.

3.3.2 Musical experience and speech-in-noise perception

The current study used a sample of participants with a range of musical experience. A musical experience score was obtained which included measures of both formal training and informal musical experience. This score was moderately correlated with speech reception thresholds in steady and modulated noise. This supports the idea that musical training might be linked with improved speech perception in noise, which has previously been reported when highly trained musicians have been compared with non-musicians (Parbery-Clark et al., 2009, 2011; Swaminathan et al., 2015). This result therefore indicates that lifelong musical training is not a requirement to observe an enhancement for speech perception in noise.

3.3.3 Musical beat perception and speech-in-noise perception

The main aim of this study was to identify specific musical skills which might underlie the reported musician enhancement for speech perception in noise and which could therefore be targeted for training.

The strongest predictor of speech-in-noise performance was musical beat perception. This skill was strongly correlated with speech reception thresholds in both steady and modulated noise, as well as with modulation masking release, even when controlling for working memory and frequency discrimination. The rhythm test also correlated with speech reception thresholds in steady and modulated noise, although a considerable part of this variance was explained by working memory.

The results suggest that beat perception could provide a useful link between musical training and speech-in-noise perception, although no direction of causation can be inferred from a correlation analysis. This issue of causation will be addressed in Chapter 6, when a beat training programme will be assessed for its impact on speech perception in noise. First, though, the focus turns to the second aim of the thesis – to investigate the mechanism by which musical beat perception might contribute to speech perception in noise.

Entrainment to a regular beat is a fundamental musical skill and an innate human ability that has been observed in infants (Honing, 2012). However, individuals do vary in how and how well they perceive a beat (Grahn and McAuley, 2009; Thompson et al., 2015), and beat perception can be improved by musical training (Slater et al., 2013).

To achieve a high score in the beat perception test, listeners must tune in to the beat of the music and form predictions about when the next beats will occur. This enables comparison of the superimposed beep positions with the predicted beats. If the beeps coincide with the expected beat positions, then they will be judged as being on the beat.

Unlike music, speech does not necessarily contain an isochronous beat. There is, however, regularity in the metric structure of strong and weak syllables in speech, and listeners are able to tap along to this regularity as they would to a beat in music (Lidji et al., 2011). It has been shown that the metric structure of speech can facilitate predictions about when the next strong syllable will occur (see Section 1.5.2; Pitt and Samuel, 1990). When listening to speech in challenging environments, such predictions could be particularly useful to focus attention at points in time when important parts of the signal are expected. People who are adept at perceiving a musical beat might also derive greater benefit from the metric structure of speech, and this might underlie the association between beat perception and speech reception thresholds observed in the current study (see Figure 3.5).

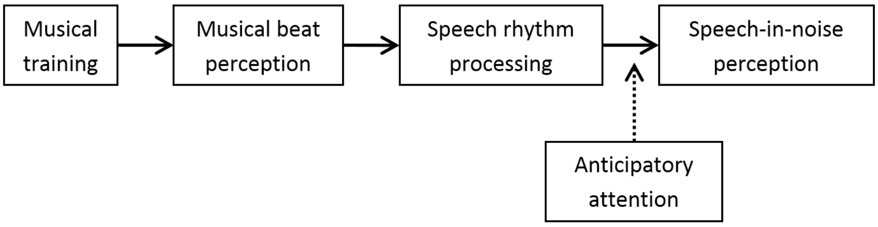


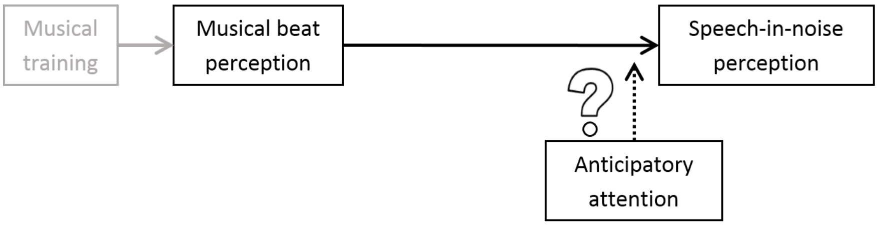
Figure 3.5: Flowchart of the proposed mechanism by which musical beat perception might aid speech-in-noise perception

It should be noted that the sentences of the matrix test all have the same syllabic structure and are therefore rhythmically predictable. It is possible, therefore, that the choice of speech test led to an enhanced correlation with beat perception. However, given the strength of the relationship, this is unlikely to be the whole story.

Chapters 4 and 5 will explore the hypothesis that musical beat perception is linked to the use of rhythm to orient attention towards points in time when a target signal is predicted to occur, and that this mechanism enhances speech perception in challenging environments.

CHAPTER 4

Rhythmic priming of anticipatory attention to targets in noise



This chapter explores the hypothesis that beat perception contributes to speech perception in noise by facilitating temporal predictions about when target words will occur. Three experiments were designed to investigate whether rhythmic priming of anticipatory attention can enhance perceptual thresholds for targets which occur at expected times in noise.

4.1 Introduction

In Section 1.9, the main research question of this thesis was broken down into three steps. The first of these was addressed in Experiment 1, and beat perception was identified as a possible link between musical training and speech-in-noise perception. The next step is to investigate the mechanism by which beat perception might enhance speech perception in noise.

In Section 3.3.3, it was hypothesised that listeners with good musical beat perception might benefit from the metric structure in speech when listening in challenging environments (see Fig 3.5). This proposed mechanism of transfer is based on two assumptions which will be tested in this chapter:

1. Anticipatory attention driven by beat-based rhythms enhances the perception of target sounds in background noise
2. Perceptual benefits of rhythmic priming are associated with musical beat perception

4.2 Experiment 2: Priming with a simple beat

4.2.1 Aims

The aim of Experiment 2 was to establish a rhythmic priming paradigm to manipulate temporal expectations in order to determine if anticipatory attention can enhance perception of targets in noise. Specifically, two tasks were included in order to build on prior research:

> *Pure-tone detection in noise* – it has previously been shown that endogenous orienting of temporal attention enhances pure-tone detection in noise (Werner et al., 2009). The first aim of the current experiment was to investigate if a similar benefit would be observed from anticipatory attention driven by rhythmic priming.
>
> *Speech perception in noise* – priming with a musical rhythm reduced reaction times to an on-time speech target in quiet (Cason and Schön, 2012). The second aim of Experiment 2 was to examine the effects of rhythmic priming on the speech reception threshold for words in noise.

4.2.2 Task design

4.2.2.1 Priming sequence

A simple isochronous sequence of tones – similar to that used by Jones et al. (2002) – was used to orient anticipatory attention. In order to ensure that temporal expectations were formed on a trial-by-trial basis rather than being built up over a block of trials, the tempo of the priming sequence was jittered. For each trial, the inter-beat interval was selected at random from a set range (600 ms ± 5%). This range of inter-beat intervals was chosen to exceed the just-noticeable difference in tempo for speech and music (Quené, 2007) while avoiding large differences between trials which might have been distracting for participants.

The aim of the experiment was to investigate priming of attention for targets in noise. Since any additional stimulus onsets might have interfered with temporal expectations, the background noise was steady and present throughout the trial. The level of the priming sequence was chosen so that it was clearly audible over the noise.

4.2.2.2 Speech perception task

A set of monosyllabic (consonant–vowel–consonant) words were chosen as the possible targets to be identified in the speech task. A key consideration in designing the speech task was deciding how to align these target words with the beat of the priming sequence. Simply aligning the targets by syllable onset would not have been sufficient to produce a perception of regularity (Patel et al., 1999). Instead, it was necessary to identify the 'perceptual centre' or 'p-centre' of each target word. This is the point within the syllable that is perceived as the moment of occurrence for that syllable.

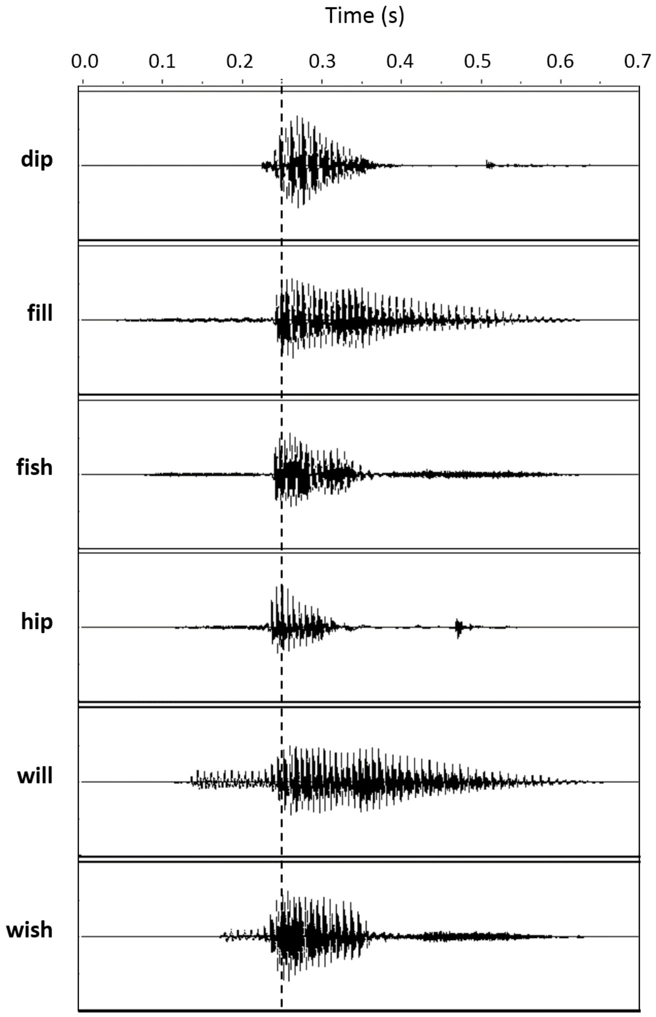


Figure 4.1: Waveforms of speech targets

There is no simple method for finding the p-centre, although various acoustical correlates and models have been suggested (Patel et al., 1999). Therefore, the p-centres for each target word were located manually as follows:

1. An initial estimate for the p-centre was taken as the onset of the vowel, as identified by examining the waveform of the target word
2. The target word was looped alongside a metronome, with the estimated p-centre aligned with the onset of each click
3. The alignment was fine-tuned, and steps 2 and 3 repeated until the target word was perceived as occurring on the beat of the metronome
4. The alignment was double-checked by a second musically trained experimenter who listened to the priming sequence plus target in quiet, for all target words and positions in a random order, and judged whether the target sounded early, on-beat or late in each case

The waveforms of a selection of target words, with the p-centres aligned (dashed line), are shown in Figure 4.1.

4.2.2.3 Tone task

A single-interval, yes/no task was used for pure-tone detection in Experiment 2. This means that on each trial the participant simply had to state whether or not they heard the target tone. Yes/no tasks can be prone to bias, in that each participant may have a tendency to answer ‘yes’ more often than ‘no’, or vice versa. This kind of bias can be avoided using a multiple-interval forced-choice task, where participants must choose the interval in which the target appeared (Kingdom and Prins, 2010). However, a multiple-interval paradigm was not suitable for the current experiment, as it would have required repetition of the rhythmic sequence to prime expectation in the second interval. This would have resulted in a long gap between the intervals which would make it difficult for listeners to compare their memory traces for each interval to make the decision at difficult SNRs.

Another alternative would be to use comparison intervals around the next two beats of the sequence, since peaks in anticipatory attention should continue to occur (Jones et al., 2002). However, the effects of anticipatory attention on subsequent beats have not previously been investigated within the same experiment so it is not clear if this would provide a fair comparison. It would also be difficult to demarcate the two time intervals for participants without interfering with the rhythmically driven temporal expectations.

For these reasons, a single-interval yes/no task was chosen, despite the possible influence of bias. Since the aim of the current experiment was to compare performance for early, on-time, and late targets, the issue of bias was actually not a critical one. If a participant has a biased response pattern, there is no reason to assume that this pattern would vary between the target conditions. Therefore, while bias would affect the absolute threshold estimates, it should not affect any differences between thresholds. In order to minimise effects of bias on the threshold estimates, catch trials were included in which no target was present. The proportion of 'yes' responses to these trials – the false alarm rate – was used when fitting psychometric functions to each participant's data.

4.2.2.4 Target positions

An isochronous priming sequence orients anticipatory attention towards subsequent beats in the sequence. Jones et al. (2002) found that temporal expectations were primed not just towards the next beat in the sequence, but that this effect also extended to the following beat as well. However, these findings were from two separate experiments so it is not possible to directly compare the effects of anticipatory attention in each case.

In the current experiment, the priming sequence consisted of six tones, or beats. For the tone-detection task, on-time targets could occur in line the seventh or eighth beat of the sequence, with early and late targets either side of these beats. This design enabled direct comparison of the effects of anticipatory attention for the two beats following the end of the priming sequence.

For the speech task, there were multiple possible target words, and these were counterbalanced across conditions to negate any differences in intelligibility. In order to maintain a comparable and feasible block length, only one beat condition was used in the speech task: on-time targets always occurred in line with the seventh beat of the sequence.

In all conditions, anticipatory attention was expected to enhance thresholds for targets occurring in line with subsequent beats of the priming sequence, compared with those for temporally displaced targets.

4.2.2.5 Estimating the perceptual thresholds

In order to examine the effects of anticipatory attention, thresholds needed to be estimated for each of the target positions. It was vital that all target positions were combined in a single block with equal probability, in order to prevent endogenous temporal orienting to a most frequent target position.

As discussed in Section 2.4.1, an adaptive procedure is the most efficient way to obtain a threshold estimate. However, for the current experiment there were arguments against the use of an adaptive staircase.

While piloting the tone-detection task, it became clear that listeners needed a regular reminder of the target sound to assist with the task. If the majority of targets were presented at difficult SNRs, as is the case with adaptive staircases, listeners reported perceiving a target in the noise signal even when it was not present.

The current experiment used monosyllabic target words, which are unlikely to be perfectly matched in perceptibility even when matched in overall intensity. As discussed in Section 2.4.1, an adaotive procedure would not be suitable for use with such stimuli.

It would have been possible to solve the first of these problems for the tone-detection task by including additional easy trials spaced throughout the staircase, or by targeting a higher threshold level. However, the second issue with the speech task meant that the use of an adaptive staircase was inappropriate. It was therefore decided to use the method of constant stimuli for both tasks.

In order to efficiently sample the psychometric functions, it was decided that the SNR levels would be set for each participant, as follows.

An adaptive procedure was used to assess a participant's performance on each target task in the absence of the priming stimuli, and SNR levels were set according to this initial estimate. Participants completed a practice block, after which the SNR levels were reassessed. If the data showed that two or more of the levels resulted in ceiling performance, and participants reported that the majority of trials were easy, the SNRs were decreased. Conversely, if the data showed that two or more SNRs resulted in floor performance (equal to guess rate or false alarm rate), and the participant reported finding the task very difficult, then SNRs were increased. When adjustments were necessary, the experimenter used the practice data to choose SNRs which would give a good threshold estimate by covering the full range of performance.

4.2.3 Methods

4.2.3.1 Participants

Participants were recruited via posters placed around the Queen's Medical Centre and University of Nottingham campus, and were naïve to the purpose of the study. Fourteen native English speakers (4 male), aged between 19 and 36 (mean age 26, standard deviation 6.1 years), with normal hearing ($\leq$20 dB HL across the standard audiometric frequencies from 250 Hz to 8 kHz) took part in this study. Participants gave their informed consent prior to starting the study and received an inconvenience allowance.

4.2.3.2 Stimuli

On each trial, the priming sequence was followed by a target sound, with a background noise present throughout the trial (ending after a random interval following the target offset). The priming sequence was clearly and comfortably audible over the background noise (5 dB SNR for speech task; 0 dB SNR for tone task).

Priming sequence

The priming sequence consisted of 6 pure tones (440 Hz frequency, 60 ms duration including 10 ms cosine on/off ramps) presented isochronously. As discussed in Section 4.2.2.1, the tempo of the sequence was selected at random for each trial, with the inter-beat interval ranging from 570 to 630 ms. This range of intervals was chosen so that differences in tempo were noticeable – to prevent expectations being built up across the block – while also ensuring that the resultant range of possible target positions in the different conditions were far from overlapping (see Figure 4.5).

Speech targets

The target stimuli were monosyllabic words recorded by a male native English speaker. There were 12 target words, each taking the form consonant–[i]–consonant. The targets were chosen so that at least one of the consonant sounds was confusable with another word in the list (see Figure 4.2). Participants responded by choosing the word they had heard from the list of 12 possible targets presented on a touch screen monitor.

dip	fib	fill	fish
hip	kill	kiss	ship
whizz	will	wish	witch

Figure 4.2: The target words used in Experiment 2

Tone target

The target tone was a 1 kHz pure-tone of 80 ms duration (including 10 ms cosine on/off ramps). Participants responding by pressing a button which corresponded with their answer: ‘yes’ when they heard the target; ‘no’ when they did not.

Background noise

For the speech task, the background was a speech-spectrum noise matching the long-term spectrum of the target stimuli, and was presented at 60 dBA. For the tone task, a background of white noise was present (at 60 dB SPL) throughout each trial.

4.2.3.3 Target positions

For the speech-perception task, target words occurred in three positions relative to the seventh beat of the priming sequence: early, on-beat or late. Early and late targets were temporally displaced by one-third of the trial inter-beat interval. The three target positions were equally likely to occur. Figure 4.3 shows a schematic of a trial with an on-beat target.

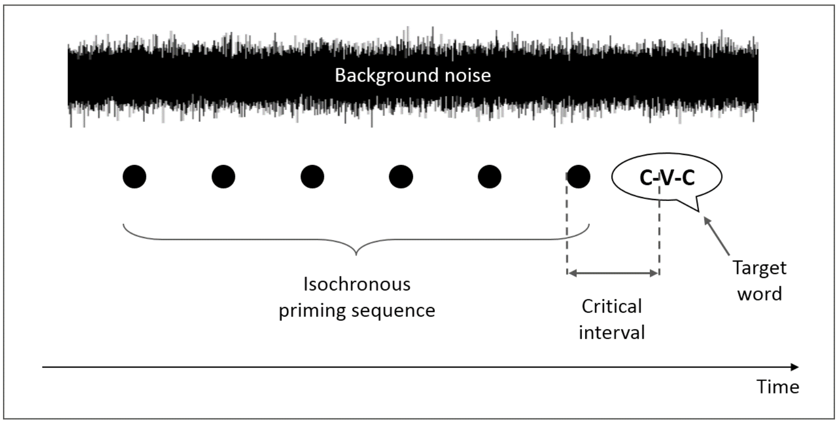


Figure 4.3: Schematic diagram of a trial in the speech discrimination task in Experiment 2

For the tone-detection task, on-time targets occurred in line with the seventh or eighth beat of the sequence, with early and late targets either side of these beats. In the early and late conditions, targets were displaced by one-quarter of the trial inter-beat interval. Figure 4.4 shows a schematic of a trial showing the six possible target positions.

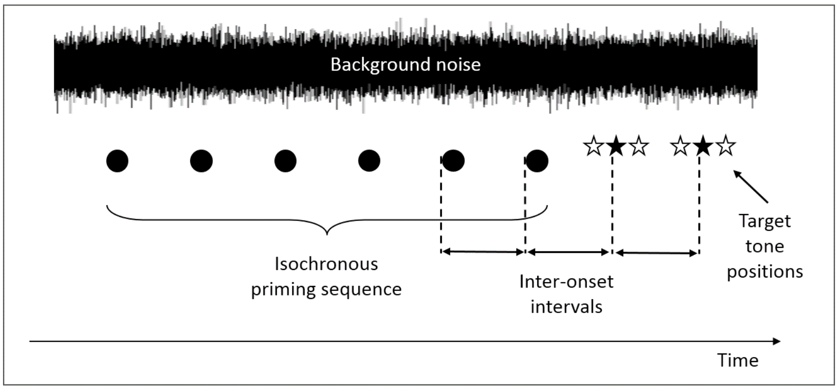


Figure 4.4: Schematic diagram of a trial in the tone detection task in Experiment 2

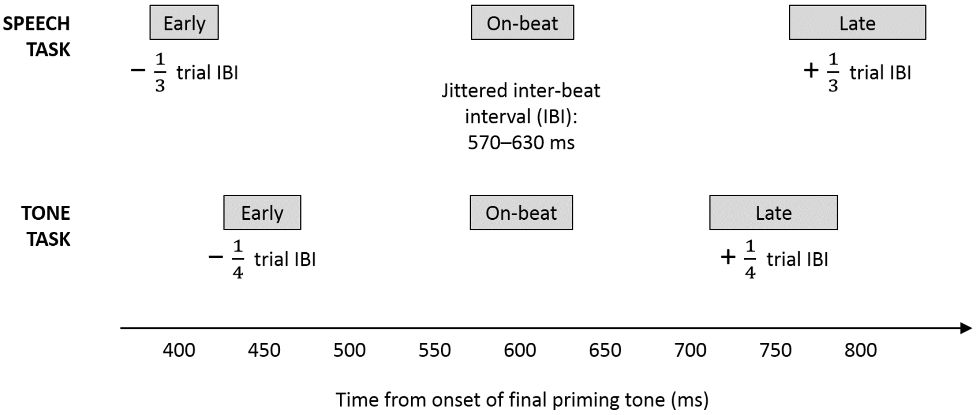


Figure 4.5: Effect on target positions of jittering the inter-beat interval

4.2.3.4 *Method of constant stimuli*

The method of constant stimuli was used, with a constant noise level and five possible SNRs for the target sound.

For the speech task, each participant completed 4 blocks of 180 trials (12 target words × 5 SNRs × 3 target positions). The order of trials was randomised within each block, and the target words were balanced across all target positions and SNRs to average out any differences in perceptibility.

For the tone task, each participant completed 4 blocks of 216 trials (5 SNRs × 6 target positions × 6 repetitions, plus 36 trials with no target present).

The order of trials was randomised within each block. No-signal trials were included to assess the rate of false alarms for each participant.

Setting levels for each participant

The SNR levels for each participant were determined using an adaptive procedure.

For the speech task, a 3-down 1-up staircase was used to estimate the 79% threshold (Levitt, 1971) for identifying the target words in noise (without the priming sequence). The average of two such thresholds (rounded to the nearest dB) was used as the second highest SNR for the speech task, with a difference of 3 dB between the other SNRs. For example, if a participant's average threshold from two adaptive staircases was –14 dB SNR, then the SNRs used in the experiment would have been –11, –14, –17, –20 and –23.

For the tone task, a 3-down 1-up staircase was used to estimate the 79% threshold for detecting the target in a 3-alternative forced choice task (without the priming sequence). Feedback was given during the adaptive procedure, to help familiarise participants with the target sound. The average of two thresholds (rounded to the nearest dB) was used as the second highest SNR for the experiment, with a difference of 2 dB between the other SNRs.

For each task, participants completed a practice block, after which the data were assessed by the experimenter. If necessary, the SNR levels were adjusted to ensure that the full range of performance would be observed during the experimental blocks.

4.2.3.5 Procedure

Testing took place in a sound-proof booth over two sessions. All auditory stimuli were presented diotically using Sennheiser HD-25 headphones, using Matlab v2008a (The MathWorks, Natick, MA).

In the first session, participants completed the speech discrimination task, including two adaptive tracks to determine SNR levels (as described above), a practice block of 30 trials, and all four blocks of the speech task, with breaks in between blocks as required.

In the second session, participants completed the tone detection task, including hearing three samples of the target in noise, two adaptive tracks (as described above), a practice block of 36 trials, and all four blocks of the tone detection task, with breaks when needed.

All tasks were self-paced in that the response triggered the start of the next trial, and participants were not required to respond within a set time limit.

Participants were instructed that the tone sequences were designed to prepare them for the next trial and were not part of the task. At the end of the second session, participants were debriefed regarding these instructions, and asked whether they paid attention to the priming sequences or simply ignored them.

4.2.3.6 Analysis

Psychometric functions were fitted to the data as described in Section 2.4.3.

The effects of rhythmic priming on the threshold of the psychometric functions were analysed using repeated-measures ANOVAs. For the speech task, the only factor entered into the analysis was target position (with 3 levels: early, on-beat, late). For the tone task, there were two within-subject factors: beat (i.e. whether the target was closest to the beat immediately following the priming sequence (Beat 1) or the one after that (Beat 2)) and target position (with 3 levels: early, on-beat, late). The performance profile across target positions was predicted to be quadratic in shape, centred around the on-beat target position (Jones et al., 2002). Polynomial contrasts were used to test this prediction and quadratic curves were fitted to the data (see Equation 2.3).

4.2.4 Results

4.2.4.1 Effect of rhythmic priming on speech perception in noise

The mean thresholds and slopes for the three target positions are given in Table 4.1.

Table 4.1: The mean thresholds and slopes for the speech perception task in Experiment 2

Target position	Mean threshold	Mean slope
	(dB SNR)	(% per dB SNR)
Early (−0.2 s from beat)	−15.3	12.8
On-beat (0 s from beat)	−15.9	11.5
Late (+0.2 s from beat)	−15.5	11.4

The repeated-measures ANOVA showed a significant main effect of target position on speech reception threshold (F(2,26) = 10.0, p = .001, partial η^2 = .44). There was a significant quadratic trend over target positions (F(1,13) = 38.2, p < .001, partial η^2 = .75). Figure 4.6 shows the mean thresholds for the three target positions, with the fitted quadratic curve. Planned comparisons (Bonferroni corrected) showed that the threshold for on-beat targets was significantly lower than that for both early (p = .001) and late targets (p = .026) as predicted. This means that rhythmic priming did enhance speech perception in noise.

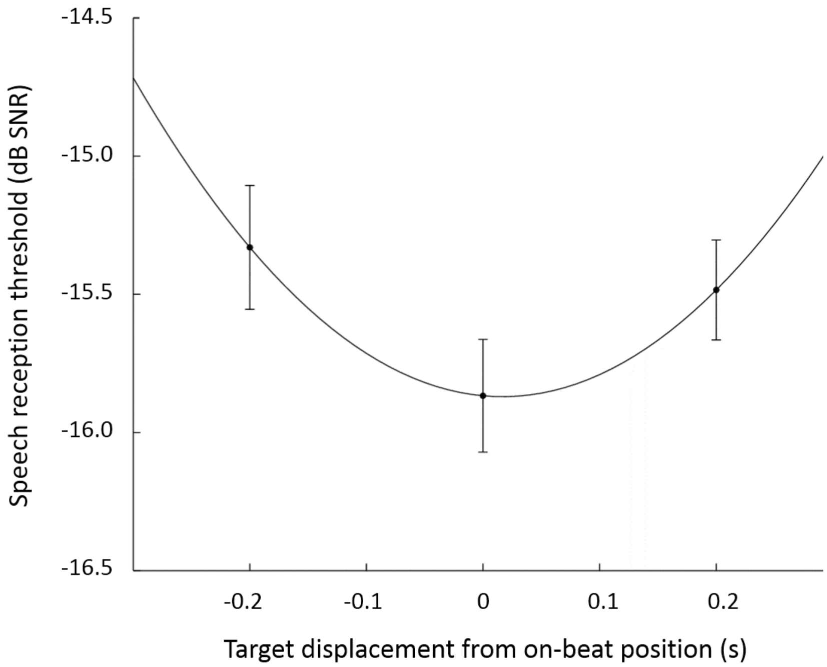


Figure 4.6: The speech task results from Experiment 2, showing mean thresholds and standard error bars for the three target positions

Perception performance for individual target words

Table 4.2 shows the percent correct performance at each SNR (all target positions combined) for each target word. There were clear differences in perceptibility between the targets, justifying the use of the method of constant stimuli over an adaptive procedure. Some words were correctly identified more often than expected even at the hardest SNRs (e.g., ship, whizz) while others were difficult to distinguish even at the easiest SNRs (e.g., fib, witch).

It is likely that certain sounds were easier to pick out of the noise. For example, ship was the only word with ‘sh’ at the start, and participants found this easy to distinguish. Similarly, whizz had the unique ‘zz’ which made it relatively easy to identify. At the other end of the scale, fib and witch also had unique sounds (‘b’ and ‘tch’ respectively) but these were apparently better masked by the background noise, and there were multiple other targets beginning with ‘f’ or ‘w’ which made a correct guess less likely. Removal of these four target words would leave eight words with more similar perceptibility.

One participant remarked that they found hearing the word ‘kill’ quite distracting, so this will also be removed for Experiment 3, along with ‘kiss’ as this word would then have no confusible sounds. This leaves six target words for use in Experiment 3: dip, fill, fish, hip, will, wish.

Table 4.2: Perception performance for the individual target words used in Experiment 2

Target word	**Percent correct identification for each SNR**					**SNRs combined**
	Hardest				Easiest	
dip	**5**	**11**	41	82	99	48
fib	13	18	**18**	**19**	**28**	**19**
fill	21	50	74	94	96	67
fish	8	19	63	89	96	55
hip	12	17	43	71	89	46
kill	15	36	77	96	100	65
kiss	22	57	89	96	99	73
ship	**39**	**68**	89	99	99	**79**
whizz	**33**	**70**	**96**	98	99	**79**
will	17	44	82	92	99	67
wish	8	27	61	79	82	51
witch	**3**	**5**	**18**	**46**	78	**30**
Words combined	16	35	63	80	89	57
Standard deviation	11	22	27	24	21	19

4.2.4.2 *Effect of rhythmic priming on pure-tone detection in noise*

The mean thresholds and slopes for the three target positions (with data from Beat 1 and Beat 2 combined) are given in Table 4.3.

Table 4.3: The mean thresholds and slopes for the tone detection task in Experiment 2

Target position	Mean threshold	Mean slope
	(dB SNR)	(% per dB SNR)
Early (−0.15 from beat)	−19.7	17.9
On-beat (0 s from beat)	−20.2	17.1
Late (+0.15 s from beat)	−19.7	17.1

The repeated-measures ANOVA showed a significant main effect of target position ($F(2{,}26) = 10.1$, $p = .001$, partial $\eta^2 = .44$). There was a significant quadratic trend over target positions ($F(1{,}13) = 24.5$, $p < .001$, partial $\eta^2 = .65$) as expected. Figure 4.7 shows the mean thresholds for the early, on-beat and late target positions. Planned comparisons showed that the threshold for on-beat targets was significantly lower than that for both early ($p = .003$) and late targets ($p = .004$) as predicted. This means that rhythmic priming did enhance tone detection in noise.

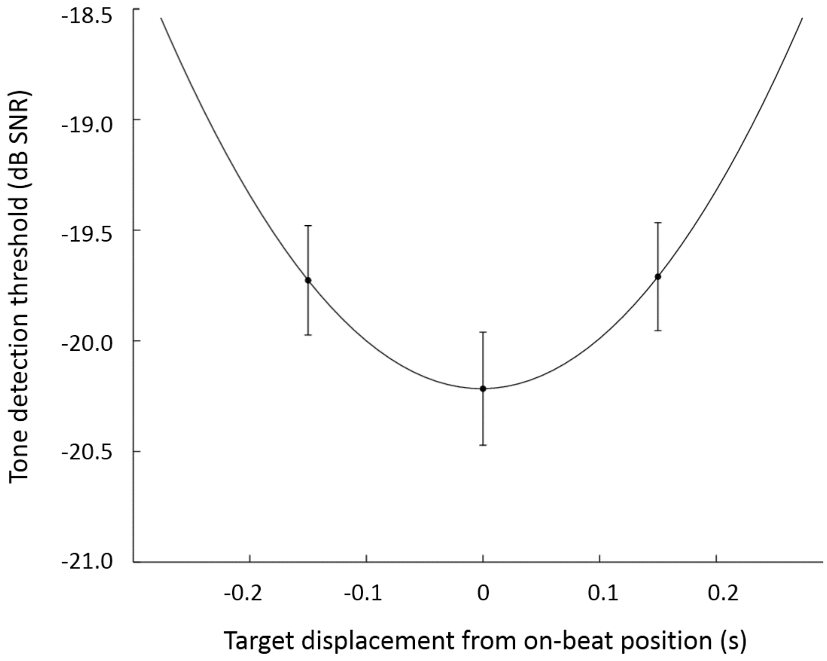


Figure 4.7: The tone detection task results from Experiment 2, showing mean thresholds and standard error bars for the three target positions

The main effect of beat (i.e. which beat the target was closest to) was not significant, but the beat by target position interaction was significant ($F(2{,}26) = 7.01$, $p = .004$, partial $\eta^2 = .35$). Separate univariate analyses for Beat 1 and Beat 2 both showed a significant main effect of target position (Beat 1: $F(2,26) = 9.39$, $p = .001$, partial $\eta^2 = .42$; Beat 2: $F(2,26) = 7.19$, $p = .003$, partial $\eta^2 = .36$) and a significant quadratic trend (Beat 1: $F(1,13) = 20.9$, $p = .001$, partial $\eta^2 = .62$; Beat 2: $F(1,13) = 6.61$, $p = .023$, partial $\eta^2 = .34$). Figure 4.8 shows the mean thresholds for all six target positions.

For Beat 1, the on-beat threshold was significantly lower than the early threshold ($p < .001$), but there was no significant difference between the on-time and late target positions ($p = .307$). For Beat 2, the on-beat threshold was significantly lower than the late threshold ($p = .019$) but not significantly different from the early threshold ($p = 1.0$). These different patterns support the decision not to use a two-alternative forced-choice task with comparison intervals based around the two subsequent beats.

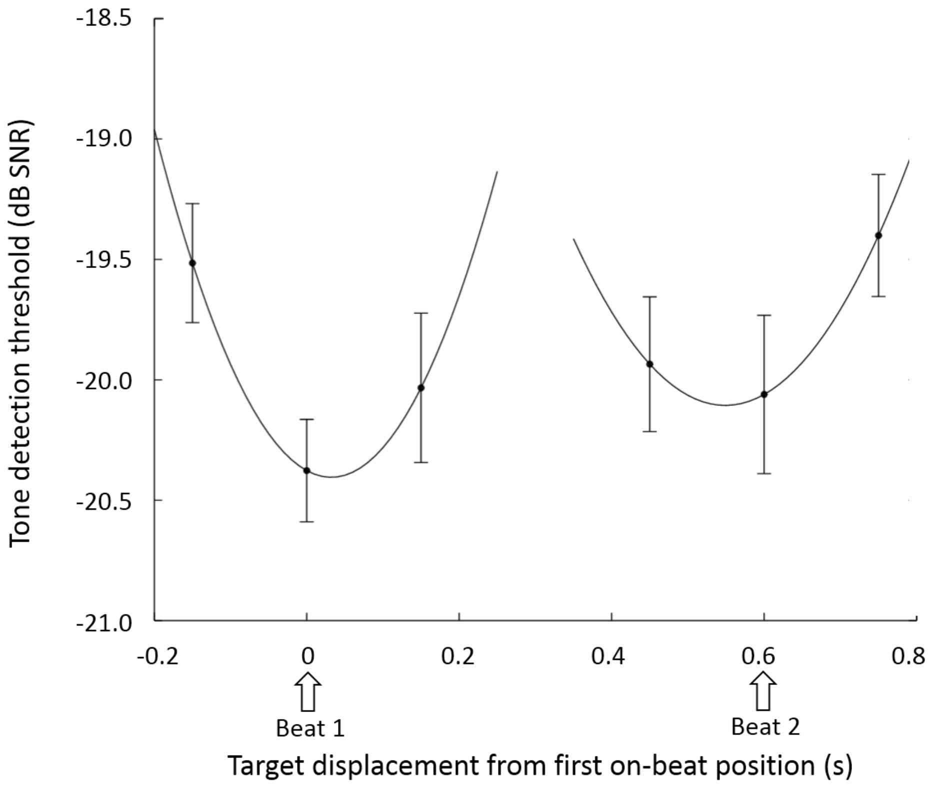


Figure 4.8: The tone detection results from Experiment 2, showing mean thresholds and standard error bars for the six target positions

4.2.4.3 Comparison of rhythmic priming effects in the two tasks

Table 4.4 contains summary statistics for the rhythmic priming effects observed in the speech and tone tasks. Comparison of the coefficients of x^2 in the fitted quadratic functions suggests that the effect of rhythmic priming was greater for pure-tone detection than for speech perception.

Table 4.4: Table showing summary statistics for the speech and tone tasks in Experiment 2. Note that the target positions differed in the two tasks, so the two benefit statistics are not directly comparable

Summary statistic	**Speech task**	**Tone task**
Priming effect^a	11.5	22.1
Mean slope^b (% per dB SNR)	11.9	17.4
Mean threshold benefit^c (dB SNR)	0.46	0.50
Equivalent performance benefit^d (% correct)	5.5	8.6

^{a} The coefficient of x^2 in the fitted quadratic
^{b} Averaged over all three target positions
^{c} Mean of thresholds for displaced targets minus threshold for on-beat targets
^{d} Mean benefit multiplied by mean slope

Another measure of priming benefit is the difference between thresholds for on-beat and displaced targets. For both tasks the improvement in threshold for on-beat targets was around 0.5 dB, although it should be noted that the early and late targets were displaced by different intervals in the two tasks, so these values are not directly comparable. This benefit can be converted to an improvement in performance by multiplying the threshold benefit by the mean slope of the threshold. The benefit for on-beat (compared to early and late) words is equivalent to a 5.5% increase in discrimination performance. The benefit for on-beat (compared to early and late) tones is equivalent to an 8.6% improvement in detection performance.

4.2.5 Discussion

In this experiment, a rhythmic priming paradigm was used to test the hypothesis that stimulus-driven anticipatory attention can enhance perception of targets in noise.

For this study, there was quite a wide age range within the relatively small sample of participants, which is not ideal. However, within the young adult age range being tested, neither thresholds nor rhythmic priming were expected to change with age. This was in fact the case, with no significant correlations observed for age and threshold or for age and priming effect for either task (all p-values $> .1$).

Rhythmic priming has previously been shown to reduce response times to a speech target presented in quiet (Cason and Schön, 2012). In the current experiment, the effects of rhythmic priming were investigated for speech targets in noise, and for perceptual thresholds rather than reaction times. The results indicate that rhythmic priming can lead to enhanced speech reception thresholds for targets occurring on the beat.

Previous research has also shown that deliberate orienting of attention to a point in time can enhance detection of a pure-tone target in noise when this target occurs in line with the temporal expectation (Werner et al., 2009). The results of the current experiment demonstrate that pure-tone detection in noise can also be enhanced by automatic orienting of temporal attention via a rhythmic sequence. Detection performance was superior for targets which occurred on future beats of the priming rhythm.

Different patterns of results were observed for targets which occurred around the first and second beats following the priming sequence. This is in contrast to a previous report (Jones et al., 2002) that performance profiles were similar for targets occurring around the next two beats of a priming rhythm . In that study, the two beat conditions were tested separately, whereas in the current study all target positions were combined within the same blocks. The results of this experiment therefore indicate that, although anticipatory attention does persist beyond the end of the priming sequence, the pattern of effects may not be consistent. In future experiments, targets will be located around a single beat, to avoid any confounds arising from the different patterns of results observed here.

As with prior rhythmic priming studies (de la Rosa et al., 2012; Jones et al., 2002), listeners were instructed that the priming sequence was not part of the task and they did not need to attend to the tones. However, during debrief, several participants reported that they had tapped along with or counted the priming tones. It is possible, therefore, that the observed attentional effect could have had an endogenous component, despite that fact that the on-beat targets occurred in only one third of the trials and were therefore not predictive (usually a condition of endogenous orienting). As no control condition was included in the current study, it cannot be concluded definitively that the observed effects were entirely due to automatic orienting of attention by the isochronous priming sequence.

The paradigm used in this experiment was successful in manipulating temporal expectations. However, there are several possible refinements to the tasks that will be discussed in the design of Experiment 3.

4.3 Experiment 3: Priming with musical rhythms

4.3.1 Aims

Experiment 2 confirmed that stimulus-driven anticipatory attention can enhance perception of both speech and tone targets in noise. However, a simple isochronous priming sequence is not representative of the complex metrical rhythms found in music or speech.

Rhythmic priming is an automatic process, somewhat comparable to the exogenous cueing discussed in Section 1.3. For an exogenous cue to successfully capture attention, it must be sufficiently salient. In rhythmic priming, the cue could be considered to be the beat of the priming sequence, so salience here could refer to the strength of the beat percept that arises as a result of the rhythmic sequence.

An isochronous sequence would result in a strong beat percept, whereas for more complex musical rhythms the beat might not be so obvious. For more complex rhythms, the strength of the priming cue could depend on the listener's ability to perceive the beat. It would then follow that the rhythmic priming effect from such rhythms should be correlated with musical beat perception.

In Experiment 3, different rhythmic sequences were used in order to compare the effects of priming with:

- simple rhythms with a strong, salient beat percept (no musical ability needed to perceive the beat)
- more complex rhythms with a less salient beat percept (musical ability needed to perceive the beat)
- non-beat rhythms with no isochronous pulse (control condition)

4.3.2 Task design

4.3.2.1 Speech stimuli

The twelve target words used in Experiment 2 resulted in a wide range of performance (see Table 4.2). To remove confounds due to variations in perceptibility, a subset of six of these words was used in Experiment 3 (see Section 4.2.4.1). These words were identified as having a similar level of perceptibility, while still containing confusable consonant sounds: dip, fill, fish, hip, will, wish.

4.3.2.2 Target positions

In Experiment 2, there were three target positions around each on-beat position. While the data are consistent with enhanced performance at the on-beat position, with just three points it is not possible to determine if the performance profile is in fact quadratic, as would be expected by the oscillatory explanation of dynamic attending theory (see Figure 1.3).

In order to examine the shape of the performance profile in more detail, five target positions were used in Experiment 3. As before, a quadratic shape was expected, centred with peak performance at the on-beat position (as reported by Jones et al. (2002)).

4.3.2.3 Priming rhythms

The priming seqences used in Experiment 3 were based on those investigated by Grahn and Rowe (2009). The rhythmic sequences were arranged in common time (i.e., 4 beats to each bar) and different methods were used to emphasise the first beat in each bar (the ‘downbeat’) in order to create the perception of a regular pulse. The interval between downbeats will be referred to as the inter-beat interval.

The first type of rhythm, referred to as ‘volume beat’, consisted of an isochronous sequence of tones in which every fourth tone was presented at a higher intensity. This is a highly salient way to emphasise the downbeat, and no musical expertise is needed to perceive the beat.

The ‘duration beat’ condition exploited the fact that changes in note lengths can be used to create emphasis during a musical sequence (Grahn and Brett, 2007). Sequences of identical tones were created such that the inter-onset intervals were equal to one-quarter, one-half, three-quarters, or one times the inter-beat interval. The intervals were arranged in a metrical structure so that each group of intervals added up to one inter-beat interval. This resulted in sequences in which an emphasised tone would be perceived on every downbeat, despite the fact that all tones were acoustically identical. This is a less salient way to create a perception of musical beat compared to the volume beat condition.

It is useful to consider these different rhythm types in the context of the beat alignment test. The test uses music from different genres and the salience of the beat varies between excerpts. For example, in the rock excerpts, drums or other percussion instruments are used to produce a loud sound on each downbeat – this is similar to the volume beat condition. Conversely, in the orchestral excerpts, there is no percussion and instead the beat percept arises from the metrical structure and relative durations of notes – similar to the duration beat condition. To perform well on the beat alignment test, the listener must be able to perceive the beat in both types of music.

Two other priming conditions were also included in this experiment: an isochronous sequence, in order to compare results to those obtained in Experiment 2; and a non-beat sequence, which was designed to act as a control condition.

It was predicted that each of the three beat conditions would result in a quadratic performance profile (with the greatest enhancement for on-beat targets), while the non-beat condition would result in a flatter performance profile. It was also predicted that musical beat ability (as measured by the beat alignment test) would correlate with the priming benefit observed for the less salient duration beat condition.

4.3.2.4 Refining the method of constant stimuli

In Experiment 2, an adaptive procedure was used to determine the SNR levels for each participant. Of the 14 participants, a majority (9 in the speech task; 8 in the tone task) were eventually tested using the same set of SNRs, with only small variations for other listeners. Examination of the performance data from Experiment 2 confirmed that a single set of SNRs would have adequately covered the range of observed thresholds. The SNRs were therefore fixed in Experiment 3.

Given the number of conditions to be tested in this experiment, the number of trials per condition needed to be minimised. A bootstrapping procedure was applied to the data from Experiment 2, as follows. The collected data were sampled at random to create a possible set of observations for a given number of repetitions, and this sampling was repeated 1000 times to obtain a mean set of results. Psychometric functions were fitted to the resampled data, and the effect of target position on threshold was analysed with a repeated-measures ANOVA. This process was repeated for different numbers of repetitions in order to determine how many repetitions were required in order to observe a significant effect of rhythmic priming.

For the speech task, it had already been decided to use a set of six target words in the current experiment. To balance these words across all conditions, the number of repetitions needed to be a multiple of six. Bootstrapping with six repetitions was not sufficient to observe a significant effect of target position ($p > .4$). Twelve repetitions, however, was sufficient to observe the quadratic priming effect for both speech and tone tasks ($p = .001$). Therefore, in Experiment 3, twelve repetitions were included for each target position and SNR combination.

4.3.3 Methods

4.3.3.1 Participants

The sample size to be used for this experiment was decided using an a priori power analysis conducted in G*Power 3 (Faul et al., 2007). Inputs were the effect size from Experiment 2 (partial η^2 was equal to 0.44 for both tasks), an alpha level of 0.05 and a desired power level of 0.8, for a repeated measures ANOVA with one group and five measures. The output suggested a sample size of 17 people. However, as the counterbalancing of conditions required a multiple of 8 participants, the power level based on 16 participants was calculated. The resulting value was 0.79 which was deemed to be sufficient.

Participants were recruited via posters placed around the Queen's Medical Centre and University of Nottingham campus. Sixteen native English speakers (6 male), aged between 18 and 24 (mean age 21, standard deviation 1.5 years) completed this experiment. They were naïve to the purpose of the study and had not previously taken part in Experiment 2. Participants were screened for normal hearing using pure tone audiometry ($\leq$20 dB HL across standard audiometric frequencies from 250 Hz to 8 kHz). Participants gave their informed consent prior to starting the study and received an inconvenience allowance for their time.

4.3.3.2 Stimuli

Priming sequences

Four priming conditions were used: isochronous, volume beat, duration beat, and non-beat. All of the tones in all of the priming sequences were pure-tones of 440 Hz frequency and 60 ms duration (including 10 ms cosine on/off ramps). The inter-beat interval was jittered randomly within a range (570–630 ms), as in Experiment 2.

The isochronous sequence consisted of seven tones, with each inter-onset interval equal to the inter-beat interval.

The volume beat sequence consisted of an isochronous sequence of tones, with each inter-onset interval equal to one-quarter of the inter-beat interval. The first, and thereafter every fourth, tone was presented at a higher volume (65 dB) than the remaining tones (55 dB). The loud tones defined the beat, and therefore the onset interval between loud tones was equal to the inter-beat interval.

In the duration beat condition, the shortest inter-onset interval was the same as that in the volume beat condition (one-quarter of the inter-beat interval). The remaining intervals were integer multiples of this duration, and intervals were arranged into groups that added up to the inter-beat interval. For example, the duration beat sequence in Figure 4.9 could be written as 2+1+1, 2+2, 3+1, 3+1, 1+3, 2+2. The relative durations of the intervals created the perception of beat, and a tone occurred on every downbeat in the sequence.

The non-beat sequences were created by altering a sequence of identical tones in which all inter-onset intervals were initially equal to one-quarter of the inter-beat interval. One third of the inter-onset intervals were reduced by 30% and one third were increased by 30%. These intervals were then arranged in a random order on each trial in order to create a sequence which had no regular beat.

Examples of these four types of sequence are shown in Figure 4.9. The vertical lines in the figure represent the beat structure, and tone onsets which are aligned with these vertical lines are on the beat. All of the priming sequences started with a tone on the first beat and ended with a final tone occurring on the seventh beat. The three beat conditions also had tones on beats two through six, whereas the non-beat condition did not.

The target stimulus occurred on or around the eighth beat, as described below.

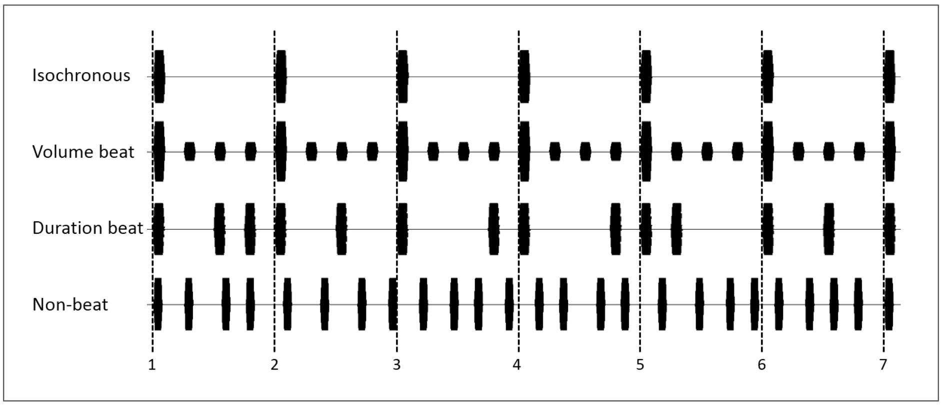


Figure 4.9: Example priming sequences from the four rhythmic conditions, with dotted lines showing the position of beats 1 to 7

Speech targets

The six target words used in Experiment 3 are shown in Figure 4.10. This subset of words were chosen from those used in Experiment 2 as they produced similar levels of perceptibility, and each contains at least one confusable consonant sound.

dip	fill	fish
hip	will	wish

Figure 4.10: The word list used in Experiment 3

Tone target

The tone target was the same as in Experiment 2 (1 kHz pure-tone, 80 ms including 10 ms cosine on/off ramps).

Background noise

The background noise was the same as in Experiment 2 (speech task: speech-spectrum noise at 60dBA; tone task: white noise at 60 dB SPL).

4.3.3.3 Target positions

For both tasks, targets occurred in five positions with equal probability. On-beat targets were aligned with the eighth beat of the priming sequence, while early and late targets were temporally displaced by either one-sixth or one-third of the trial inter-beat interval (see Fig 4.11).

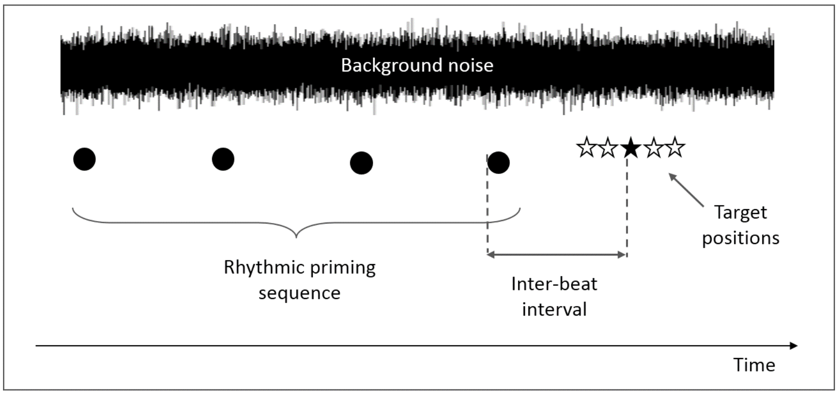


Figure 4.11: Schematic of the task used in Experiment 3, showing the five target positions in relation to a shortened isochronous sequence

Due to a programming error, the targets in the duration beat condition were presented slightly later than intended. The delay was equal to one-quarter of the trial inter-beat interval minus 60 ms. So, for an interval of 600 ms, the targets occurred 90 ms later than intended – meaning that 'on-beat' targets were actually presented just 10 ms before the late target position, etc. This did not impair the analysis of priming effects as thresholds were fitted for each position, and the actual displacements were used for fitting quadratic curves to the data. All results figures display the actual target positions which were presented.

4.3.3.4 *Method of constant stimuli*

The method of constant stimuli was used, with a constant noise level and five possible SNRs for the target sound.

For the speech task, each participant completed 2 blocks for each of the 4 priming conditions. Each block consisted of 150 trials (6 target words × 5 SNRs × 5 target positions). The five SNRs were fixed for all participants: –12, –14, –16, –18, –20 dB SNR. The order of trials was randomised within each block, and the target words were balanced across all target positions and SNRs.

For the tone task, each participant completed 2 blocks for each of the 4 priming conditions. Each block consisted of 180 trials (5 SNRs × 5 target positions × 6 repetitions, plus 30 trials with no target present). The five SNRs were fixed for all participants: –16, –18, –20, –22, –24 dB SNR. The order of trials was randomised within each block. No-signal trials were included to assess the rate of false alarms for each participant.

4.3.3.5 Subjective beat ratings of priming sequences

The aim of this experiment was to compare rhythmic priming using sequences of varying beat salience. To determine if the manipulations were successful, a subjective rating exercise was completed at the end of the final session, separate from the priming task. Listeners heard eight tone sequences (two for each rhythm type) in a randomised order, and judged each on a scale from 1 (no regular pulse) to 10 (obvious beat). The two ratings for each rhythm type were averaged to give a score which represented how easy it was to hear the beat.

4.3.3.6 Musical beat perception

Participants' ability to perceive a musical beat was assessed using the auditory-only section of the Beat Alignment Test (Iversen and Patel, 2008). Details were the same as in Experiment 1 (see Section 3.2.2, page 62).

4.3.3.7 Procedure

Testing took place in a sound-proof booth over four sessions. All auditory stimuli were presented diotically using Sennheiser HD-25 headphones, using Matlab v2008a (The MathWorks, Natick, MA).

In each session, participants completed both blocks of the speech task for one priming condition, and both blocks of the tone task for a different priming condition. The order of priming conditions for each task was counterbalanced across participants.

Prior to starting each task, participants completed five practice trials with audible targets in order to familiarise themselves with the task, the target sound, and the sequence type. An additional practice block (25 or 30 trials for speech or tone tasks respectively) was included only in the first session.

All tasks were self-paced in that the response triggered the start of the next trial, and participants were not required to respond within a set time limit.

As in Experiment 2, participants were instructed that the tone sequences were designed to prepare them for the next trial and were not part of the task. At the end of the final session, participants completed the subjective beat ratings and beat alignment test, and were debriefed about their behaviour during the priming task.

4.3.3.8 *Analysis*

Psychometric functions were fitted to the data as described in Section 2.4.3.

For one participant, there was cause for concern regarding the concentration level during the non-beat condition of the tone task. Inspection of the raw data confirmed the listener had lost focus during this block, resulting in a low detection rate even at the highest SNRs. The data from this participant for this condition were therefore excluded from analysis.

The effects of rhythmic priming on the threshold of the psychometric functions were analysed using repeated-measures ANOVAs. Due to the exclusion of one participant in the non-beat condition, and the error in presented target positions for the duration beat condition, separate analyses were run for the four priming conditions. The single factor of target position (5 levels) was entered into the analysis for both tasks. Polynomial contrasts were used to examine the performance profiles, and quadratic curves were fitted to the data (see Equation 2.3).

Finally, Pearson correlations were used to analyse the relationship between musical beat perception and the priming effect in each beat condition.

4.3.4 Results

4.3.4.1 *Subjective beat ratings*

The scores show that the different rhythmic accents had the desired effect (see Figure 4.12). The isochronous and volume beat conditions scored very highly, confirming that the beats in these sequences were easy to hear. The duration beat condition scored lower, with more variability, meaning that people differed in how easy they found it to hear the beat in these sequences. This suggests that the beat was indeed less salient in the duration beat condition.

Beat salience cannot, however, explain the variability observed for the non-beat condition, since there was no isochronous beat to be perceived. While the non-beat rhythms were rated the lowest of the four, as expected, two participants judged these sequences as having a clear beat. It is possible that this reflects a misunderstanding of the instructions or the description of a regular pulse. It could also be that these listeners failed to perceptually distinguish between the isochrony in the beat rhythms and the lack of it in the non-beat rhythms, and they genuinely perceived what they thought was a regular pulse in the non-beat rhythms.

The subjective rating scores were not normally distributed, so non-parametric analyses were used. The Friedman test was significant ($\chi^2(3) = 44.2, p < .001$). Post hoc analysis using Wilcoxon signed-rank tests with Bonferroni corrections confirmed that all pairwise comparisons were significant (Isochronous vs Volume beat: Z = -2.23, p = .026; Isochronous vs Duration beat: Z = -3.52, $p < .001$; Isochronous vs No beat: Z = -3.52, $p < .001$; Volume beat vs Duration beat: Z = -3.53, $p < .001$; Volume beat vs No beat: Z = -3.52, $p < .001$; Duration beat vs No beat: Z = -2.83, p = .005).

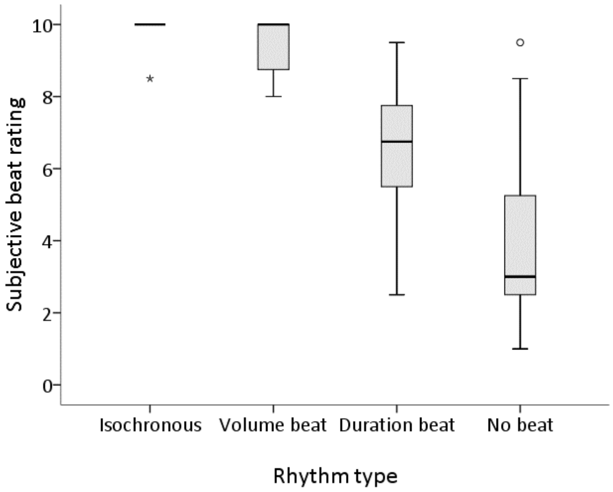


Figure 4.12: Boxplots of the subjective beat ratings for the four priming rhythms. Participants rated each sequence on a scale from 1 (no discernible beat) to 10 (easy to hear beat).

4.3.4.2 Effect of rhythmic priming on speech perception in noise

The mean thresholds for the four priming conditions and five target positions are shown in Figure 4.13. Repeated-measures ANOVAs revealed no significant effects of target position on threshold for any of the four conditions (Isochronous: F(4,60) = .10, p = .98; Volume beat: F(4,60) = .29, p = .88; Duration beat: F(4,60) = 1.20, p = .32; No beat: F(4,60) = 2.32, p = .07).

This means that the rhythmic priming had no effect on the perception of speech targets in Experiment 3. Figure 4.14 shows the results of the isochronous priming condition in Experiments 2 and 3 for comparison. Summary statistics for these two tasks are given in Table 4.5.

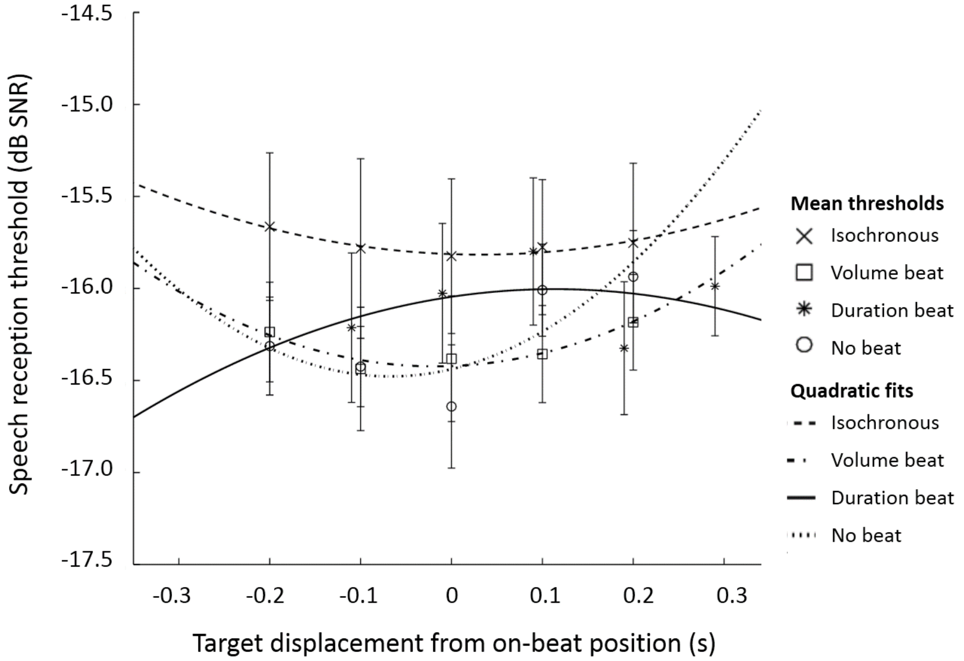


Figure 4.13: The speech task results from Experiment 3, showing mean thresholds and standard error bars for the five target positions; quadratic curves have been fitted to the data for clarity although no significant relationships were observed

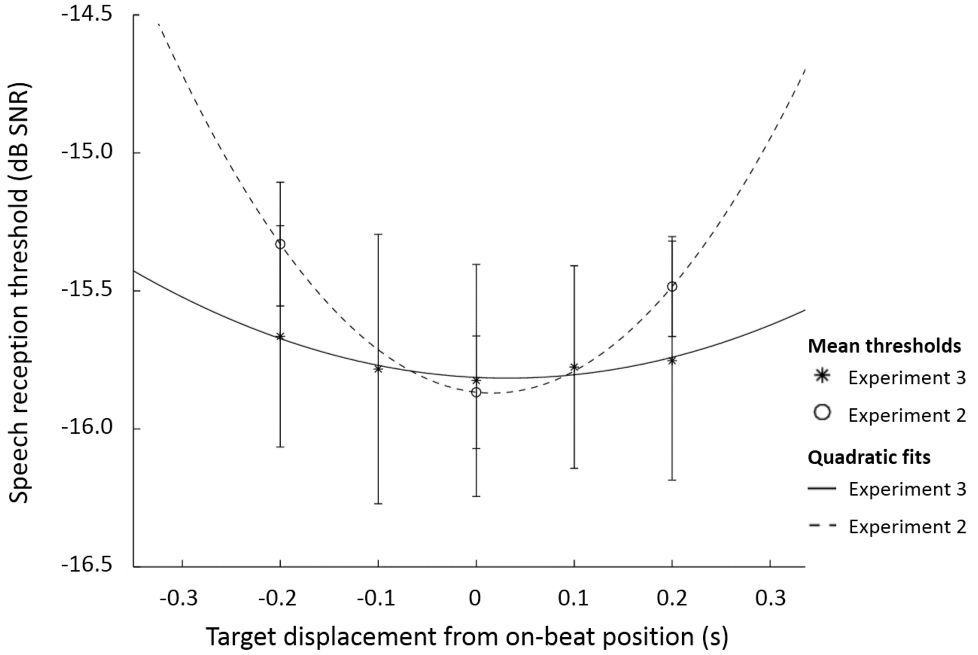


Figure 4.14: The speech task results for the isochronous priming condition from Experiments 2 and 3, showing mean thresholds and standard error bars for each target position

Table 4.5: Table showing summary statistics for the isochronous condition of the speech discrimination tasks in Experiments 2 and 3

Summary statistic	Experiment 2	Experiment 3
Mean priming effect^{a}	11.5	2.7 (n.s.)
Standard deviation	7.0	20.2
Mean slope^{b} (% per dB SNR)	11.9	14.7
Mean threshold benefit^{c} (dB SNR)	0.46	0.12 (n.s.)
Equivalent performance benefit^{d} (% correct)	5.5	1.7

[a] The coefficient of x^2 in the fitted quadratic

[b] Averaged over all target positions

[c] Mean of thresholds for displaced targets minus threshold for on-beat targets

[d] Mean benefit multiplied by mean slope

Despite the similarities between the tasks used in the two experiments, the results appear to be quite different: the Experiment 2 results show a clear quadratic trend, with significant benefit for on-beat targets; the Experiment 3 results show a much flatter profile with no significant effects of target position. Possible reasons for these different patterns will be discussed below.

4.3.4.3 Effect of rhythmic priming on tone detection in noise

The mean thresholds for the four priming conditions and five target positions are shown in Figure 4.15. Repeated-measures ANOVAs revealed a significant effect of target position on threshold in each of the four priming conditions (Isochronous: $F(4,60) = 7.67$, $p < .001$, partial $\eta^2 = .34$, with Greenhouse-Geisser correction applied; Volume beat: $F(4,60) = 5.52$, $p = .001$, partial $\eta^2 = .27$; Duration beat: $F(4,60) = 16.5$, $p < .001$, partial $\eta^2 = .52$; Non-beat: $F(4,56) = 2.96$, $p = .027$, partial $\eta^2 = .18$).

For all four conditions, the performance profile was significantly quadratic in shape (Isochronous: $F(1,15) = 38.0$, $p < .001$, partial $\eta^2 = .72$; Volume beat: $F(1,15) = 10.8$, $p = .005$, partial $\eta^2 = .42$; Duration beat: $F(1,15) = 27.7$, $p < .001$, partial $\eta^2 = .65$; Non-beat: $F(1,14) = 9.37$, $p = .008$, partial $\eta^2 = .40$). The non-beat condition appears to have resulted in a shallower curve, as predicted, although the priming effect (see Table 4.6) is not significantly different from the other conditions (all pairwise comparisons with $p > .3$).

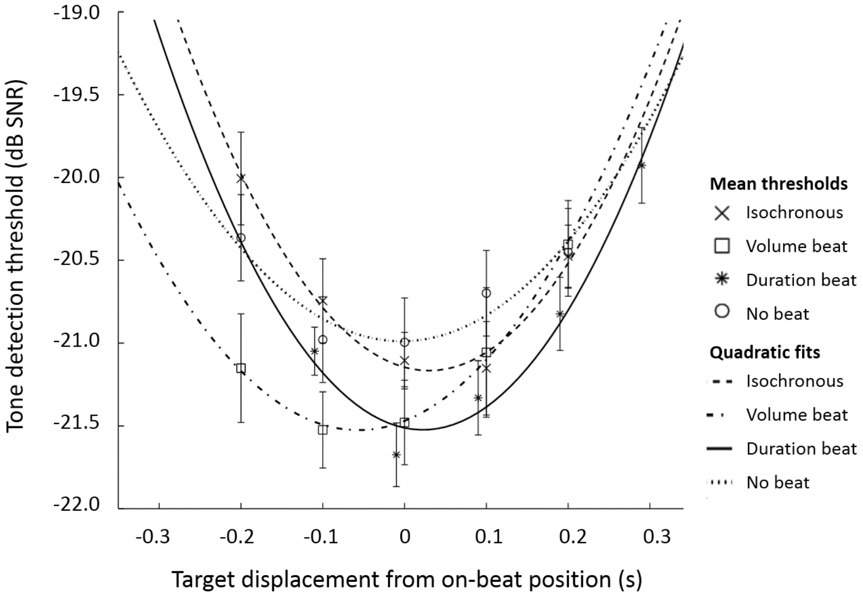


Figure 4.15: The tone-detection task results from Experiment 3, showing mean detection thresholds with standard error bars for the five target positions in the four priming conditions

Table 4.6: Table showing summary statistics for the tone-detection task in Experiment 3

Summary statistic	Isochronous	Volume beat	Duration beat	No beat
Priming effect[a]	22.5	17.4	22.9	14.5
Mean slope[b] (% per dB SNR)	17.9	17.8	18.5	18.1
Mean threshold benefit[c] (dB SNR)	0.86	0.70	0.84	0.59
Equivalent benefit[d] (% correct)	15.5	12.5	15.6	10.7

[a] The coefficient of x^2 in the fitted quadratic

[b] Averaged over all target positions

[c] Mean of thresholds for very displaced targets minus threshold for on-beat targets

[d] Mean benefit multiplied by mean slope

The results from the isochronous priming condition for Experiments 2 and 3 are shown in Figure 4.16 and summarised in Table 4.7. Unlike for the speech task, the priming effects observed for the tone-detection task in the two experiments were very similar.

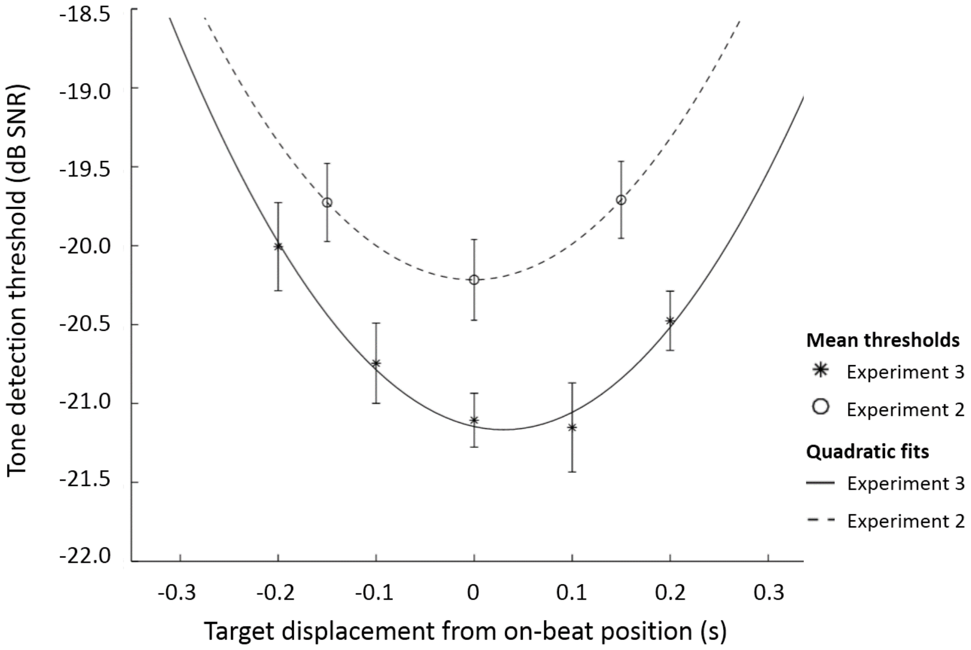


Figure 4.16: The tone-detection task results for the isochronous priming condition from Experiments 2 and 3, showing mean thresholds and standard error bars for each target position

Table 4.7: Table showing summary statistics for the isochronous condition of the tone-detection tasks in Experiment 2 and 3

Summary statistic	Experiment 2	Experiment 3
Priming effect[a]	22.1	22.5
Mean slope[b] (% per dB SNR)	17.4	17.9
Mean threshold benefit[c] (dB SNR)	0.50	0.50
Equivalent performance benefit[d] (% correct)	8.6	9.0

[a] The coefficient of x^2 in the fitted quadratic

[b] Averaged over all target positions

[c] Mean of thresholds for displaced targets minus threshold for on-beat targets; comparable thresholds (± 0.15 s) estimated from quadratic graph for Experiment 3

[d] Mean benefit multiplied by mean slope

4.3.4.4 *Musical beat ability*

Table 4.8 shows the Pearson correlation coefficients for the relationships between beat perception score and priming effect for the three beat conditions. As predicted, when the priming sequence had a less salient beat (duration beat condition), the priming effect was correlated with musical beat perception (r = .48, p = .030 (one-tailed); see Fig 4.17).

The cocor program (Diedenhofen and Musch, 2015) was used to run comparative analyses of the correlations for the most salient beat condition (isochronous) and the least salient beat condition (duration beat). The correlation coefficient between these two priming effects was 0.21 (p=.22). As hypothesised, this difference was significant, with beat perception more strongly associated with the priming effect in the less salient duration beat condition (example analyses from cocor: Hotelling's $t = 1.89$, $df = 13$, $p = .04$; Williams' $t = 1.87$, $df = 13$, $p = .04$; Dunn and Clark's $z = 1.76$, $p = .04$).

Table 4.8: Pearson correlation coefficients between beat perception and rhythmic priming effects

Correlations	Isochronous	Volume Beat	Duration Beat
Beat perception	–.08	.11	.48*

*p<.05 (one-tailed)

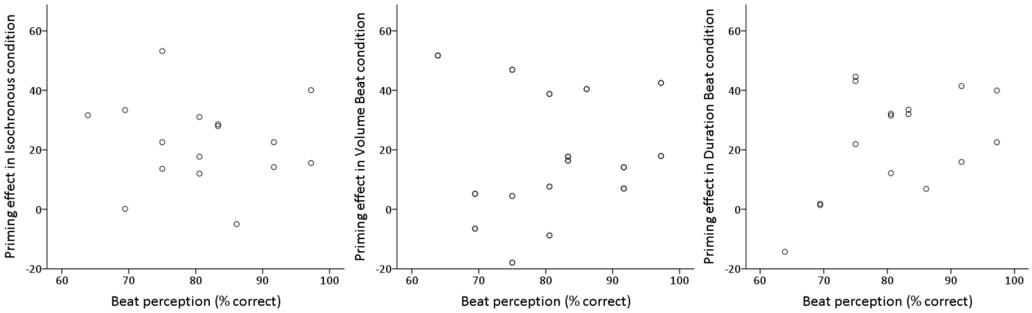


Figure 4.17: Scatter plot showing the association between musical beat ability (as measured by the Beat Alignment Test) and the priming effect in the three beat conditions

4.3.5 Discussion

The aim of Experient 3 was to compare anticipatory attention driven by different types of musical rhythms. It was hypothesised that musical beat perception would influence the size of effect observed for a priming sequence with a less salient beat.

4.3.5.1 Speech discrimination task

There was no significant effect of rhythmic priming on the perception of speech targets in noise. This was the case even in the isochronous condition which was comparable to that used in Experiment 2 (for which an effect was observed).

There were a number of changes from Experiment 2 to Experiment 3 which could have had an effect on the results:

- Six target words instead of 12
- Five target positions instead of three
- Four priming conditions instead of one
- Fewer repetitions for each condition at each SNR
- A different sample of participants

With five target positions in Experiment 3, it may be that any enhancement was diluted by the overlap of speech stimuli with other target positions. This would not have been an issue in the tone task since the target tones are considerably shorter than the target words. This possibility will be taken into account in the design of Experiment 4.

Experiment 3 was conducted over four separate sessions and each participant completed a total of 16 blocks of priming tasks, compared to two sessions of four blocks in Experiment 2. Most participants completed the study without problems, but a few complained about boredom at having to repeat the task this many times. Perhaps understandably then, during debrief participants reported quite different behaviours from those in Experiment 2.

Most participants reported that they were simply ignoring the tone sequences and just listening out for a speech sound (this possiblity will be investigated in Experiment 4). A few participants claimed that they were focusing specifically on the background noise to tune out the tone sequences. Although rhythmic priming is an automatic process that does not require deliberate attention (Jones et al., 2002), there may be a difference between passively listening to the sequence and actively ignoring it.

This behaviour is in stark contrast to that reported by participants in Experiment 2, some of whom counted or tapped along to the priming tones, despite being told that these sequences were not part of the task. As discussed in Section 4.2.5, this behaviour may have enhanced the priming effect by adding an endogenous component on top of that predicted from automatic processing of the priming rhythm. This was not the case in Experiment 3. The rhythmic cues were informative in only one-fifth of trials – compared to one-third of trials in the previous experiment – which might have further discouraged endogenous orienting of attention.

It is therefore possible that the priming effect observed for the speech task in Experiment 2 was due in part to endogenous orienting to the priming rhythms, rather than purely automatic, stimulus-driven, anticipatory attention as hypothesised. Alternatively, it may simply be that the participants in Experiment 2 were more likely to be influenced by a rhythmic prime than those recruited for Experiment 3, although the findings for the tone-detection task, below, suggest that that was not the case.

Another issue is that the bootstrapping procedure – to determine the required number of repetitions – and the power analysis – to determine the required sample size – were based on the results of Experiment 2. With multiple differences between the two experiments, any of which could have influenced results as discussed, it may be that these numbers were not in fact sufficient to observe a significant effect of rhythmic priming for speech targets.

4.3.5.2 Tone detection task

Priming with musical rhythms had a significant effect on detection thresholds for pure tones in white noise. Detection was enhanced for targets occurring on or close to the next beat of the priming sequence, and the performance profiles were quadratic in shape as predicted.

When the beat of the rhythmic priming sequence was less salient (duration beat condition), and therefore required some musical expertise to perceive, the size of the priming effect was associated with musical beat perception ability. Moreover, this correlation was significantly greater than that for beat ability and priming by isochronous sequences. This result supports the hypothesis that listeners with good beat perception can benefit from underlying, complex rhythms (such as those found in music and speech) which orient anticipatory attention towards points in time when important parts of the signal are likely to occur.

The non-beat condition was intended to be a control which would not induce rhythmic priming. However, the performance profile in this condition was also quadratic, albeit slightly – if not significantly – flatter than for the beat conditions. Irregular sequences have been reported to cue temporal attention (de la Rosa et al., 2012), and some participants did report hearing regularity even in the non-beat sequences. This suggests that these sequences may not have been an effective control for examining the effects of rhythmic priming. An alternative control sequence will be tested in Experiment 4.

4.4 Experiment 4: Priming with speech sounds

4.4.1 Aims

After the speech task of Experiment 3, participants reported ignoring the priming tones and instead listening out for a speech sound. This strategy was possible because the tones and targets were acoustically distinct, and so selective attention could be oriented to the frequency characteristics of the target voice. This may have overshadowed any orienting of temporal attention. To test this possibility, Experiment 4 used a similar paradigm but replaced the tones of the priming sequence with a syllable sound in the same voice as the target words.

4.4.2 Task design

The speech discrimination task from Experiment 3 was used here, with just two rhythm conditions: duration beat and non-beat. The duration beat condition was chosen as this was associated with musical beat ability in Experiment 3, and the non-beat condition was designed as a control.

The duration beat sequences were adapted by substituting each of the tones with a speech sound of the same duration. These sequences were therefore rhythmically identical to those used in Experiment 3, but the priming sounds and target words were acoustically similar (spoken by the same talker). The intention was to discourage participants from completely ignoring the priming sequences.

The non-beat sequences consisted of just two speech sounds, timed to match the first and last beats of the duration beat sequence, with a long gap in between. These sequences therefore offered participants the same preparation time as the duration beat condition, but with no possibility that a regular beat could be perceived.

In order to reduce the overlap of target positions due to the length of the speech targets, the target positions used here were further apart than those used in Experiment 3.

4.4.3 Methods

4.4.3.1 Participants

Participants were recruited via posters placed around the Queen's Medical Centre and University of Nottingham campus. Fourteen native English speakers (5 male), aged between 18 and 23 (mean age 19.4, standard deviation 1.7 years) completed this experiment. They were naïve to the purpose of the study and had not previously taken part in Experiment 2 nor 3. Participants were screened for normal hearing using pure tone audiometry ($\leq$20 dB HL across standard audiometric frequencies from 250 Hz to 8 kHz). Participants gave their informed consent prior to starting the study and received an inconvenience allowance for their time.

4.4.3.2 Stimuli

The speech task, target words and background noise were identical to those used in Experiment 3. Instead of a pure tone, the sound used to create the priming sequences was a 60 ms excerpt (including 10 ms cosine on/off ramps) of the syllable "ba", extracted from the same corpus as the target words (i.e., recorded by the same speaker).

Two priming conditions were used: duration beat and non-beat. The duration beat rhythms were identical to those used in Experiment 3; the non-beat sequences consisted of the first and final (7th) beats only. The inter-beat interval was jittered randomly within a range (570–630 ms), as in the previous experiments.

4.4.3.3 Target positions

Targets occurred in five positions with equal probability. On-beat targets were aligned with the eighth beat of the priming sequence, while early and late targets were temporally displaced by either one-quarter or one-half of the trial inter-beat interval.

4.4.3.4 Method of constant stimuli

The method of constant stimuli was used, with a constant noise level and five possible SNRs for the target sound. Each participant completed 2 blocks for each of the 2 priming conditions. Each block consisted of 150 trials (6 target words × 5 SNRs × 5 target positions). The five SNRs were fixed for all participants: –12, –14, –16, –18, –20 dB SNR. The order of trials was randomised within each block, and the target words were balanced across all target positions and SNRs.

4.4.3.5 Procedure

Testing took place in a sound-proof booth in a single session. All auditory stimuli were presented diotically using Sennheiser HD-25 headphones, using Matlab v2008a (The MathWorks, Natick, MA).

Participants completed both blocks of the speech task for one priming condition, and then both blocks for the other priming condition. The order of priming conditions was counterbalanced across participants.

Prior to starting the first condition, participants completed five trials with audible targets, then a practice block of 25 trials, in order to familiarise themselves with the task, the target sound, and the sequence type. For the second condition, participants just completed five practice trials to demonstrate the priming sequence.

All tasks were self-paced in that the response triggered the start of the next trial, and participants were not required to respond within a set time limit. As in the previous experiments, participants were instructed that the tone sequences were designed to prepare them for the next trial and were not part of the task.

4.4.3.6 Analysis

Psychometric functions were fitted to the data as in the previous experiments (see Section 2.4.3). The effects of rhythmic priming on the threshold of the psychometric functions were analysed using repeated-measures ANOVAs.

4.4.4 Results

The mean thresholds for the two priming conditions and five target positions are shown in Figure 4.18. Repeated-measures ANOVAs revealed no significant effects of target position on threshold for either condition (Duration beat: $F(4,52) = 1.45$, $p = .25$, with Greenhouse-Geisser correction applied; Non-beat: $F(4,52) = 1.49$, $p = .25$, with Greenhouse-Geisser correction applied).

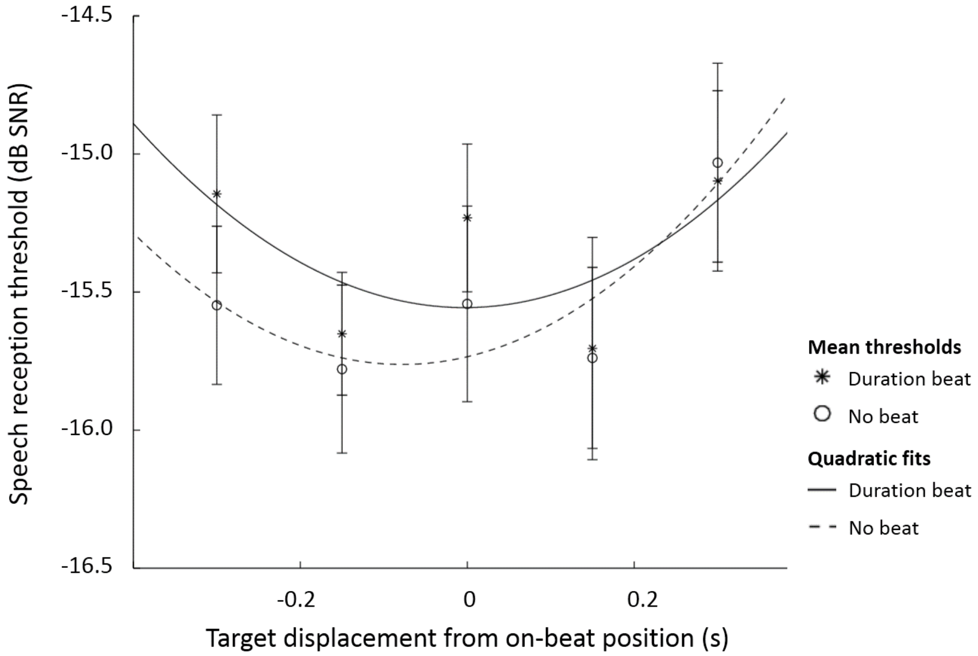


Figure 4.18: The speech task results from Experiment 4, showing mean thresholds and standard error bars for the five target positions; quadratic curves have been fitted for clarity although no significant effects were observed

Examination of each participant's results suggested that there may be individual differences in performance profiles. Figure 4.19 shows individual results from six representative participants. A few participants demonstrated the predicted pattern of results, while others showed a range of different profiles. A greater sample size would be needed to examine these different patterns and possible reasons for them. However, these results demonstrate that individual differences should be taken into account where possible, especially when the priming rhythm (duration beat) was expected to produce a range of performance (linked to musical beat ability).

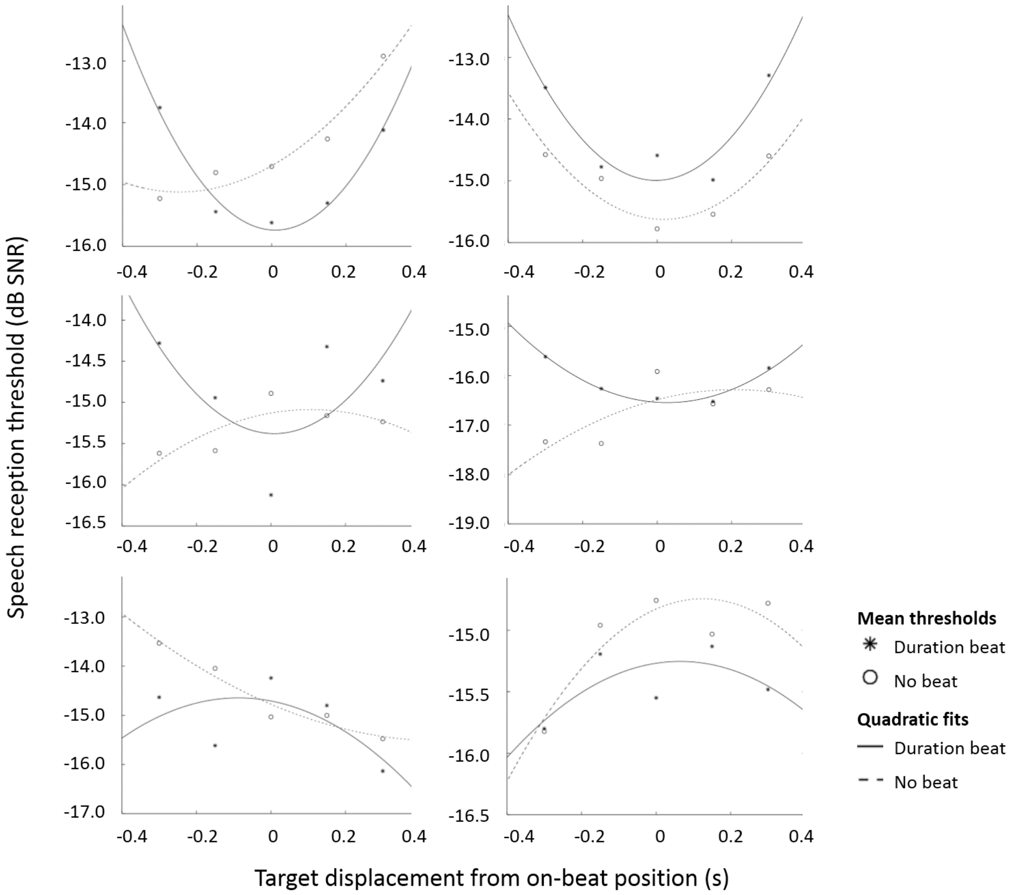


Figure 4.19: The speech task results from Experiment 4 for six participants

4.4.5 Discussion

In Experiment 3, no significant effect of rhythmic priming was observed for the speech discrimination task. It was proposed that any potential benefit of temporal expectations may have been overshadowed by the participants' reported selective attention to speech sounds.

Experiment 4 was designed to test this possibility by using speech sounds within the priming rhythms. There was no significant benefit for on-beat targets, meaning that rhythmic priming did not enhance speech perception even when the priming and target sounds were acoustically similar. Individual differences may have influenced the results – particularly as the duration beat condition was deliberately chosen as it was predicted to be associated with musical beat ability. However, the idea that participants were ignoring the tone sequences in Experiment 3 does not seem to sufficiently explain the findings.

It is possible that rhythmic priming does not automatically enhance speech perception, and that the benefit observed in Experiment 2 was purely due to endogenous orienting of temporal attention. It is worth noting, however, that there is evidence of rhythmic priming reducing reaction times in phoneme detection tasks (Cason and Schön, 2012; Meltzer et al., 1976; Quené et al., 2005). It may be that entraining to speech meter can make speech processing more efficient, and in a continuous speech-in-noise situation this would be beneficial. Such an enhancement would not have been observed in the studies presented in this chapter as reaction times were not collected and the stimuli were too short to see a benefit over time.

It is also likely that if rhythmic priming is used during speech perception, then it would be driven by speech meter in a continuous manner (see Section 1.5.2). Using a musical rhythm to prime a single monosyllabic target would not be the best way of observing such a mechanism. The next chapter will therefore investigate the effects of anticipatory attention on the perception of target words within a sentence context.

4.5 Summary

The aims of this chapter were to investigate whether priming with a regular rhythm can enhance perception of targets in noise, and whether observed benefits would be associated with musical beat ability.

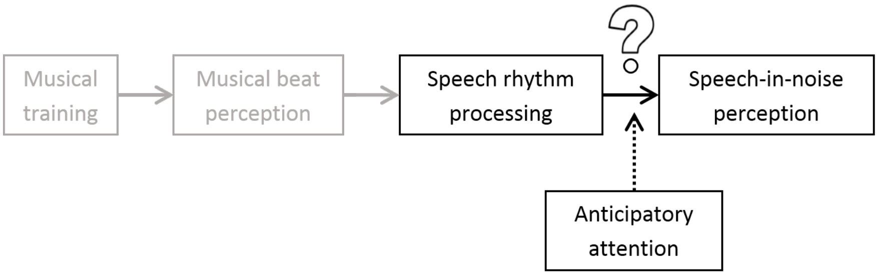
Anticipatory attention driven by rhythmic priming sequences had a small but significant benefit for the detection of a pure-tone target in white noise. When the target occurred on or close to the next beat of the priming sequence, detection thresholds were lower than for targets which occurred far from this expected time-point.

When the beat of the rhythmic priming sequence was less salient and therefore required some musical ability to perceive, the size of the attentional benefit was associated with musical beat perception ability.

These results support the hypothesis that listeners with good beat perception benefit from underlying rhythm which generates predictions about when important parts of the signal will occur, and therefore benefit from anticipatory attention. It remains to be seen whether predictions based on speech meter can enhance speech perception in noise, and this will be the focus of the next chapter.

CHAPTER 5

Rhythmic priming of attention during speech listening



When listening to speech in background noise, spatial location and voice characteristics can be used to orient attention to a target speaker. In other words, knowing where *and* who *the speaker is can enhance perception of speech in noise. This chapter explores the hypothesis that listeners also benefit from speech meter to orient temporal attention to the expected occurrence of a target, i.e.,* when *it will occur. Consideration is also given to the development of rhythmic priming as a mechanism for enhancing speech perception in noise during childhood.*

5.1 Introduction

The experiments in Chapter 4 demonstrated that:

1. rhythmic priming can enhance perception of targets in noise
2. the magnitude of effect is associated with musical beat perception when the priming rhythm contains an implicit rather than salient beat.

Experiment 5 was designed to investigate whether anticipatory attention driven by speech meter can also enhance perceptual thresholds for speech in background noise. If this is the case, then temporally displaced targets should not be perceived as well as those which occur at their natural point in a sentence context.

An additional aim of Experiment 5 was to investigate whether children and adults achieve similar benefits from rhythmic priming for speech in noise.

In Section 1.6.1, the development of speech perception in noise during childhood was discussed in terms of the underlying skills and the various cues that can aid perception. In summary, although children's perception of speech in noise is hindered by still developing sensory and cognitive systems, they are able to take advantage of various cues. Children benefit from spatial release from masking, modulation masking release, and linguistic context. It remains to be seen whether they will also benefit from rhythmic priming.

Musical beat perception has been observed in infants (Honing, 2012), so rhythmic priming benefits might be observed for young children. On the other hand, beat perception also develops with experience (Thompson et al., 2015; Slater et al., 2013), so rhythmic priming benefits might increase with age. In the latter case, it could be hypothesised that musical beat training might speed development of speech perception in noise during childhood by enhancing the benefit of priming attention via speech meter.

5.2 Experiment 5

5.2.1 Aims

It has been shown that listeners orient temporal attention to stressed syllables and that this improves reaction times to phoneme targets when listening to speech in quiet (Pitt and Samuel, 1990; Quené et al., 2005). Experiment 5 was designed to investigate whether anticipatory attention driven by speech meter can also enhance perceptual thresholds for speech in background noise.

The second aim of Experiment 5 was to compare performance of children and adults in order to explore the developmental trajectory of rhythmic priming as a mechanism to aid speech listening in adverse conditions.

5.2.2 Task design

5.2.2.1 Speech stimuli

As discussed above, the beneficial effects of temporal orienting depend on the predictions that can be made from the priming context. The greatest effects have been observed when the preceding speech contains a clear alternating stress pattern and temporal regularity (Pitt and Samuel, 1990; Quené et al., 2005).

The aim of this chapter was to investigate rhythmic priming in a sentence context, so the word lists used in previous studies would not have been suitable. The Coordinate Response Measure (Bolia et al., 2000) was identified as a good candidate for this study as the simple stimuli are suitable for use with children (with numbers as the target words). In addition, the carrier phrase ('Ready Baron, go to red...') is inherently rhythmic and can be easily manipulated to increase the temporal regularity of stressed syllables. The procedure for recording the stimuli in order to enhance the rhythmic cues will be described below.

5.2.2.2 Estimating the perceptual thresholds

The children were recruited as part of the annual Summer Scientist event at the University of Nottingham, and the time available for testing each child was limited. As discussed in Section 2.4.1, an adaptive procedure would provide a relatively quick threshold estimate but this may not be reliable for a speech task with targets that are not identical in terms of perceptibility. Therefore, the method of constant stimuli was used again here, but with four possible SNRs instead of five, in order to reduce the number of trials needed. Suitable levels for each age group were identified during piloting.

The time constraints also influenced the choice to use just two target positions: on-time and late (early targets would have overlapped with the carrier phrase). It was predicted that thresholds for on-time targets would be better than those for late targets.

5.2.2.3 Age-specific predictions

In previous studies, group comparisons have revealed interesting results, with 8 years appearing to a be a critical age in development (e.g, Bonino et al., 2013; Nishi et al., 2010; Stuart, 2005, 2008). For example, Stuart (2005, 2008) reported that speech perception in quiet reached adult levels by age 8, while speech perception in noise matured beyond age 11 years. Other studies have reported that 8–10 year-old children perform similarly to adults for some masker conditions, but for other maskers they perform worse than adults but still better than 6–7 year-old children (Bonino et al., 2013; Nishi et al., 2010). It was therefore decided to compare three age groups: younger children (6–7 years), older children (8–11 years), and adults (18–40 years).

It was predicted that speech thresholds would improve with age. Further, it was predicted that all groups would benefit from rhythmic priming and that the magnitude of the priming effect would increase with age.

5.2.3 Methods

5.2.3.1 Participants

Adult participants were recruited via posters from the University of Nottingham student population and the general public, and they received an inconvenience allowance for taking part. All adult participants were native English speakers with normal hearing, defined as pure-tone audiometric thresholds of $\leq$20 dB HL across octave frequencies from 250 Hz to 8 kHz.

Children were recruited as part of an annual event run by the Department of Psychology at the University of Nottingham. Children completed short studies in return for tokens which could be spent on games and other treats. The children's hearing was not objectively assessed during this event, but no hearing problems were reported by their parents on a background questionnaire.

Children were split into two age groups: 6–7 and 8–11 years. Further details for the three age groups are given in Table 5.1.

Table 5.1: Participant data for the three age groups in Experiment 5

Age group	*n*	Mean age (s.d.)
6 to 7 years	26 (13 male)	6.98 (.50)
8 to 11 years	41 (26 male)	9.71 (.98)
Adults (18–40)	20 (3 male)	20.9 (5.1)

5.2.3.2 *Stimuli*

The speech stimuli were based on those used in the Coordinate Response Measure (Bolia et al., 2000). Sentences of the form 'Ready Baron, go to red one now' were recorded by a female speaker for target numbers one through nine, excluding seven (as it is the only disyllabic number in the range). The talker was instructed to speak the final three words as separate units in order to avoid coarticulatory information either side of the target number. The speaker listened to a metronome during recording to ensure a consistent tempo (120 beats per minute) and to emphasise the regular rhythm of the sentences. The word 'now' was spoken on beat 7, in order to constrain the length and intonation of the target number (see Figure 5.1), but this word was subsequently removed so that the target number was the final word.

The recordings were equalised for root mean square level and then cut to separate out the target number and remove the word 'now'. Multiple tokens were recorded for each target, but variability in the quality of the recordings meant that for two targets there was only one usable token. It was therefore decided to choose the single best recording for each target number. The criteria for selecting tokens included clarity of speech, lack of coarticulation and lack of other noise. Similarly, a single recording of the carrier phrase ('Ready Baron, go to red') was chosen to act as the prime. The selected recording was clearly spoken with the correct rhythmic structure and a salient 'beat' of stressed syllables, in order to provide strong cues for driving temporal attention.

On each trial, the prime was followed by one of the target numbers, which occurred either at its original position (aligned with beat 6) or after a pause of 350 ms (see Figure 5.1). The length of pause was chosen so as to create a noticeable gap (no overlap of target positions) but also occur well before the next beat in the sequence (which may also be attended).

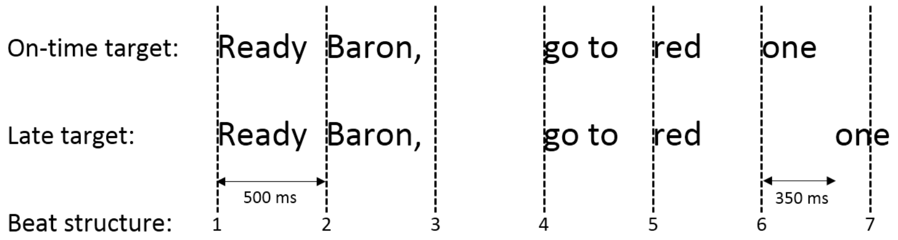


Figure 5.1: Schematic diagram of the stimuli and task used in Experiment 5

The noise masker was a steady speech-spectrum noise (ICRA, track 1; Dreschler et al., 2001) and was present throughout each trial. As in Chapter 4, a steady noise was used so that it did not contain any temporal information that could distract from the task. The noise level was constant at 60 dBA with the priming phrase presented at 0 dB SNR so that it was clearly audible on every trial. The SNR of the targets was varied to obtain a threshold estimate as described below.

5.2.3.3 Procedure

All auditory stimuli were presented diotically through Sennheiser HD-25 headphones, using Matlab v2008a (The MathWorks, Natick, MA). Participants used a touch screen monitor to indicate which number they had heard from the eight options.

For the adult group, testing took place in a sound-proof booth. This facility was not available for the child groups, but the level of background noise incorporated into the task was sufficient to mask any external noise and allow the children to focus on the task.

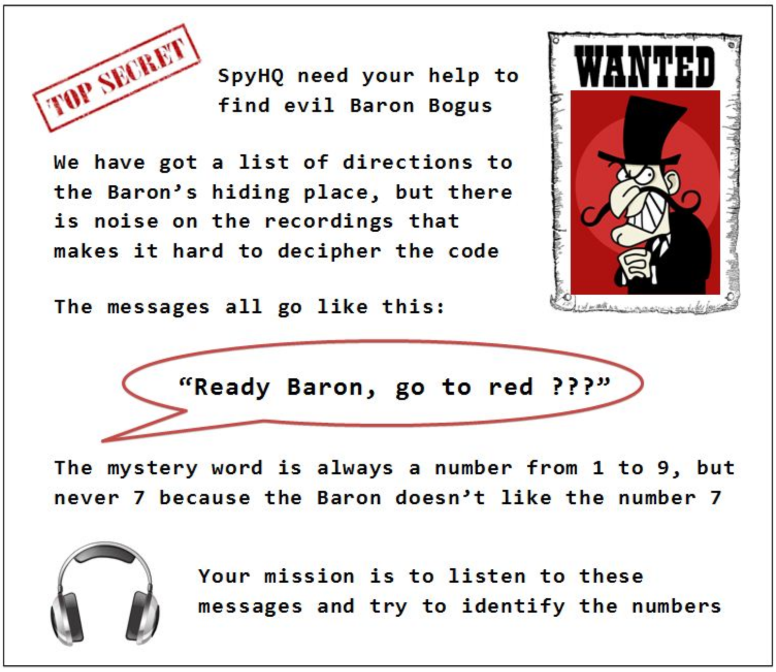
The method of constant stimuli was used with a constant noise level (60 dBA) and four possible SNRs for the target. The levels for each group were determined during piloting: for the children, targets were presented at 0, –5, –10 and –15 dB SNR; for the adults, targets were presented at –5, –10, –15 and –20 dB SNR.

At the start of the session, participants completed 5 familiarisation trials at the highest SNR, followed by a practice block of 15 trials (5 trials at each of the three remaining SNRs). All targets were on-beat during these practice trials, and the data were not included in the analysis.

Participants then completed a single experimental block of 128 trials (8 target words × 4 SNRs × 2 target positions × 2 repetitions). The order of trials was randomised and the target words were balanced across all target positions and SNRs to average out any differences in perceptibility.

All tasks were self-paced in that the response triggered the start of the next trial, and participants were not required to respond within a set time limit. The task took about 15 minutes to complete, and the children were offered a short break twice during the block.

The task was presented to the children as a spy game, in which they needed to decode secret messages. The instruction screen is shown in Figure 5.2.



SpyHQ need your help to find evil Baron Bogus

We have got a list of directions to the Baron's hiding place, but there is noise on the recordings that makes it hard to decipher the code

The messages all go like this:

"Ready Baron, go to red ???"

The mystery word is always a number from 1 to 9, but never 7 because the Baron doesn't like the number 7

Your mission is to listen to these messages and try to identify the numbers

Figure 5.2: Screenshot of the participant instructions for Experiment 5

5.2.3.4 Analysis

Psychometric functions were fitted to the data using the Palamedes toolbox for Matlab (Kingdom and Prins, 2009).

Logistic curves were initially fitted to the data as in Chapter 4. However, visual inspection of the graphs revealed some asymmetry in the data which meant that the logistic function was not a good fit in this case. A much better fit was obtained using Gumbel curves, with the minimum and maximum values of the function defined to be the guess rate (0.125) and an assumed lapse rate of 0.01, respectively. Gumbel curves were therefore fitted to the data and estimates obtained for the speech reception threshold and a measure of the slope of the function for each of the two target position for each participant (see Equation 5.1).

$$f(x;\alpha,\beta) = 1 - \exp(-10^{\beta(x-\alpha)}) \tag{5.1}$$

The data for each age group were then inspected for outliers. Two children from the 8–11 year-old group were excluded from further analysis as their thresholds were more than three standard deviations away from the group mean. One of these children performed far worse than their peers, possibly due to an underlying hearing problem or a lack of concentration during the task. The other performed far better than the rest of their age group. This child was the oldest in the group and this level of performance may have been a true measure of ability. However, as the estimated threshold fell outside the range of SNRs measured for the children, the threshold estimate may not have been accurate for this participant.

The effect of rhythmic priming on the speech threshold was analysed using a repeated-measures ANOVA with age group and target position entered as factors.

5.2.4 Results

The mean thresholds for the three age groups and two target positions are given in Table 5.2 and shown in Figure 5.3. As expected, thresholds improved with age, and the ANOVA revealed that the main effect of age group was significant ($F(2,82) = 14.4$, $p < .001$; $\eta^2 = .26$). Bonferroni-corrected pairwise comparisons were all significant (younger vs older children $p = .005$; younger children vs adults $p < .001$; older children vs adults $p = .020$).

As predicted, thresholds for on-time targets were better than those for late targets. The main effect of target position was significant ($F(1,82) = 81.1$, $p < .001$; $\eta^2 = .50$).

There was also a significant interaction effect on threshold ($F(2,82) = 3.94$, $p = .023$; $\eta^2 = .09$). Inspection of Figure 5.3 revealed that the two child groups showed similar amounts of benefit from priming while the adult group showed a greater priming effect. This suggested that the interaction was driven by differences between the older children and adults. A follow-up ANOVA with just these two age groups was conducted to test this observation. A significant interaction of age group and target position did indeed occur between the older children and adults ($F(1,57) = 7.84$, $p = .007$; $\eta^2 = .12$). Improvement in threshold was greater for on-beat targets than for late targets, suggesting further development of rhythmic priming mechanisms beyond 11 years of age.

Table 5.2: Means (and standard deviations) for the threshold parameter, α (dB SNR; see Equation 5.1)

Age group	On-time targets	Late targets
6 to 7 years	−13.03 (1.74)	−11.73 (1.75)
8 to 11 years	−14.27 (1.46)	−12.98 (1.67)
Adults	−16.03 (1.72)	−13.54 (2.24)

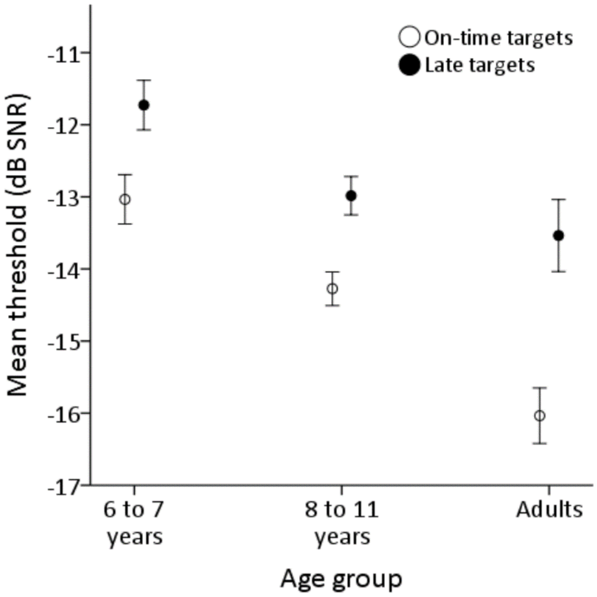


Figure 5.3: Means (and standard error bars) for the threshold parameter for each age group and each target position

Table 5.3 shows the summary statistics for the three age groups. The benefit of rhythmic priming was greater for adults than children, while the two child groups produced similar results.

Table 5.3: Table showing summary statistics for Experiment 5

Summary statistic	6 to 7 years	8 to 11 years	Adults
Mean slope[a] (% per dB SNR)	7.10	7.24	5.79
Mean threshold benefit[b] (dB SNR)	1.31	1.29	2.50
Equivalent performance benefit[c] (% correct)	8.24	9.60	15.06

[a] Averaged over both target positions
[b] Difference between on-beat and late thresholds
[c] Mean benefit multiplied by mean slope

To investigate whether the choice of age groups influenced the findings, Pearson correlations were used to examine the relationships between age and threshold and between age and priming benefit for all of the children combined (see Figure 5.4). While thresholds improved with age as expected (r=–.40, p=.001), there was no correlation between age and priming effect (r=–.08, p=.54). These results are in line with the group comparisons, and suggest that while children as young as 6 years old do benefit from rhythmic priming during speech listening, further development of this mechanism occurs beyond 11 years of age.

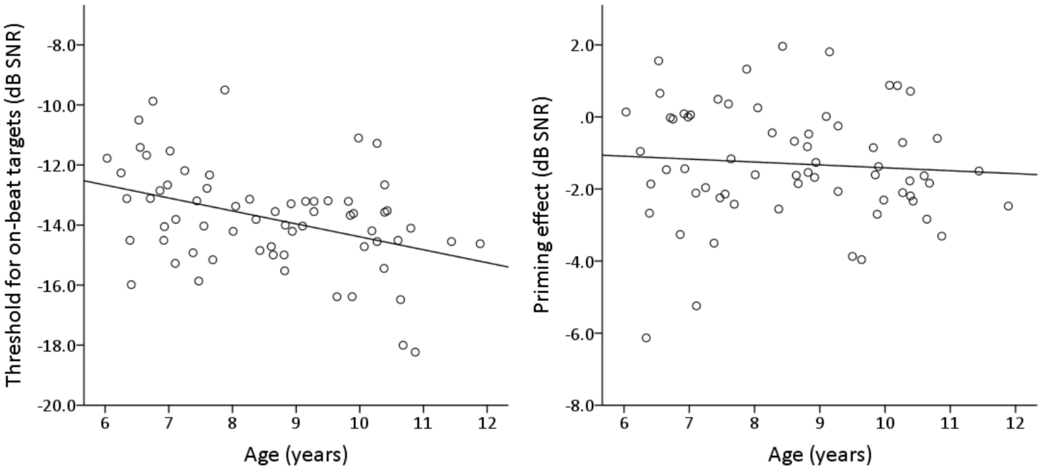


Figure 5.4: Scatter graphs of the relationships between age and threshold and between age and priming effect

5.3 Discussion

The aims of this experiment were to investigate whether temporal attention driven by speech meter enhances perception of speech in noise, and to explore how this mechanism develops during childhood.

There was a significant effect of target position, with all age groups achieving better thresholds for on-time targets than for late targets. This suggests that the rhythmic information contained in the carrier phrase was sufficient to orient temporal attention to the expected target position.

Although all age groups exhibited a priming effect, the benefit was greatest for the adult group. Within the child groups, the priming benefit did not increase with age, suggesting that – at least for the simple stimuli used here – development of the rhythmic priming mechanism occurs outside of the measured age range (6–11 years).

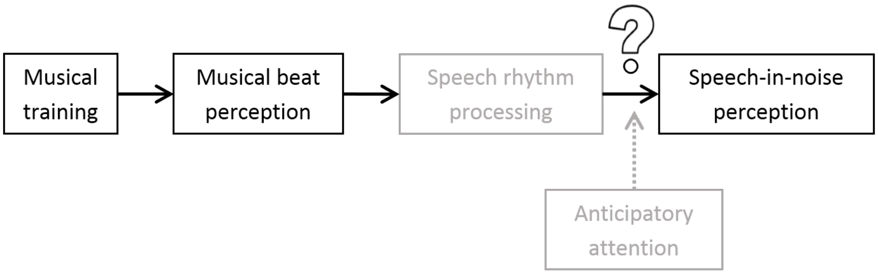
The results of the current study may not generalise to everyday speech listening situations. The stimuli used here were manipulated to increase the chances of observing rhythmic priming effects. A deliberate choice was made to sacrifice ecological validity for this preliminary exploration of the hypothesis.

Another consideration is that the carrier phrase used to orient attention was identical on each trial. There is evidence that prior knowledge of the rhythmic structure of a sentence can aid perception of a final target word. When listeners hear a musical prime prior to a sentence with matching rhythm, they are quicker to respond to a target phoneme (Cason et al., 2015). Even reading a written carrier phrase (minus the final target word) prior to hearing a sentence in noise enhances perception of the target word (Freyman et al., 2004). In the current study, the prime was identical each time, so the listeners knew both the rhythmic and semantic context of the carrier phrase. It is therefore possible that temporal expectations were built up over the course of the block rather than for each individual trial. If this was the case, then the results would still support the hypothesis that orienting temporal attention enhances speech perception in noise, but further research would be needed to test if on-line temporal predictions are formed when listening to novel speech.

Further studies are also needed to explore rhythmic priming driven by more complex and more natural speech stimuli. For example, a follow-up study could use multiple carrier phrases with different rhythmic structures, and remove the manipulation to ensure isochrony. The use of a more complex rhythm – in which a regular 'beat' is difficult to perceive – might also help to highlight developmental differences that were not observable with the simple isochrony used in the current study.

CHAPTER 6

Training musical beat perception



Results from the preceding chapters suggest that targeting musical beat perception – particularly its role in orienting temporal attention – could provide an effective intervention for speech perception in noise. These findings are used in the current chapter to guide the selection of a suitable training method. The effectiveness of the training programme is evaluated for older adults, as this group are often reported to have difficulties understanding speech in background noise.

6.1 Introduction

The ultimate goal of the current research is to evaluate a musical training programme for improving speech perception in background noise. The studies presented in the previous chapters explored the link between musical ability and speech perception in noise, in order to inform the design of an efficient, targeted training programme.

In Chapter 3, musical beat perception was identified as a key skill to target for training. Beat perception is linked to the ability to form predictions about the timing of future events. It was hypothesised that good beat perceivers benefit from rhythmic priming which orients temporal attention to important parts of an auditory signal. The experiments in Chapters 4 and 5 provided evidence in support of this hypothesis.

These findings will be considered below in the discussion of a suitable training programme to target beat perception skills. However, suitability also depends on the population to be trained. To assess whether musical training could help those who struggle with speech perception in adverse conditions, it was decided to target a population who are often reported to struggle with this task – older adults (see Section 1.6.2).

6.1.1 Training musical beat perception

Beat perception is a fundamental human ability that has been observed in infants (Honing, 2012), but it can also be improved via musical training (Slater et al., 2013). For example, when listening to complex rhythms – such as the duration beat sequences used in Experiment 4 – musicians are more likely than nonmusicians to perceive the beat (Grahn and Rowe, 2009).

A key feature of beat perception is how it relates to movement. When listening to music, people often spontaneously move along to the beat, and regular auditory rhythms activate motor areas of the brain even in the absence of movement (Grahn and Brett, 2007).

This cross-modal relationship works in both directions: movement also influences auditory perception of the beat. When listening to ambiguous rhythms, movement can influence which of two possible beat structures is perceived (Phillips-Silver and Trainor, 2005, 2007). Tapping along to the beat of a priming sequence also improves the accuracy of judgements about whether subsequent events occur on the beat (Manning and Schutz, 2013), suggesting that moving to the beat aids the orienting of anticipatory attention.

Movement also aids the process of searching for a beat in a rhythm sequence with no salient accents, and this is especially true for non-musicians (Su and Pöppel, 2012). When asked to perform this task just by listening, trained musicians were able to internally generate a beat, but non-musicians found it difficult to establish a stable beat. When movement was encouraged during the beat-finding phase, the two groups achieved similar levels of performance (Su and Pöppel, 2012).

It appears to be the case that audio-motor synchronisation plays an important part in musical training for beat perception, and after sufficient training beat perception can be achieved without overt movement. This is supported by the finding that musicians display greater connectivity between auditory and motor areas of the brain during a beat-finding task (Grahn and Rowe, 2009). It has also been shown that audio-motor musical training leads to more robust changes in the auditory cortex compared to auditory-only training (Lappe et al., 2008, 2011).

Together these findings emphasise the importance of using multimodal training when targeting beat perception. Synchronising movements to music will therefore play a key role in the training programme to be used in this study.

The training programme must also be suitable for use with older adults, and must achieve the levels of engagement and enjoyment that make musical training an attractive prospect for therapeutic interventions (as discussed in Chapter 1). With this goal in mind, established methods of musical training were explored to see if a suitable candidate could be found. While all approaches to teaching music include some element of beat training, one method stood out due to its focus on experiencing rhythm and beat through movement – Dalcroze Eurythmics.

6.1.1.1 Dalcroze Eurhythmics

Developed by Émile Jaques-Dalcroze in the early 1900s, Dalcroze Eurhythmics is a long established method of teaching musical concepts through movement. This approach is practised worldwide, has been shown to improve rhythmic abilities in children (Zachopoulou et al., 2003), and is suitable for use with older adults (Trombetti et al., 2011).

Dalcroze lessons comprise a variety of individual, pair and group tasks. Typical activities include: walking in time to improvised piano music and responding to changes in tempo; clapping to one subdivision of the beat while walking in time with another; throwing, bouncing or rolling balls in time with the beat (Frego et al., 2004; Seitz, 2005). Many of the activities are also cognitively demanding, requiring multitasking to continue the ongoing movement while sustaining auditory attention in order to react quickly to changes in the music or verbal instructions to switch between two alternative movements (Kressig et al., 2005; Trombetti et al., 2011).

The cognitive aspect of the Dalcroze approach has been exploited to investigate potential benefits for older adults. Declines in dual-task ability in older adulthood can lead to an increased risk of falling, as it becomes difficult to perform a concurrent task while walking (Kressig et al., 2005; Trombetti et al., 2011). Older adults with a long history of practising Dalcroze Eurythmics show less stride variability under dual-task conditions than their peers (Kressig et al., 2005). Six months of weekly Dalcroze classes led to improvements in gait variability under dual-task conditions for a group of older adults compared to a control group, and the benefit was still evident six months after training finished (Trombetti et al., 2011). A secondary analysis of this study reported that the training group also showed decreased anxiety and improved cognitive function compared to the control group (Hars et al., 2013).

In summary, Dalcroze Eurythmics offers an established approach to teaching musical skills that has been used successfully with older adults. The approach places a great emphasis on audio-motor synchronisation which was identified above as a key requirement for training beat perception. The wide variety of possible activities and the social aspect of including pair and group work should also satisfy the requirement for an enjoyable musical training programme.

Having identified Dalcroze Eurythmics as a potential training technique for this study, the next step was to consult a qualified Dalcroze teacher – who has experience working with older adults – to aid with the design and delivery of the training programme. She confirmed that Dalcroze techniques were indeed appropriate for the intended purpose of the training, and that activities could be adapted to specifically target beat perception skills.

6.2 Experiment 6

6.2.1 Aims

The aim of Experiment 6 was to evaluate the impact of short-term musical beat training on speech perception in noise for a group of older adults.

6.2.2 Methods

6.2.2.1 Participants

Nine native English speakers (2 male; age range 51–75, mean age 67.0, standard deviation 10.1 years) completed the study. They were recruited via posters and word of mouth from the general public and they received an inconvenience allowance for taking part.

Two further participants were initially recruited but had to withdraw due to personal reasons prior to the start of the training programme. All nine participants who began the training programme went on to complete the study.

The Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) was used to screen for mild cognitive impairment. All participants scored at least 26 out of 30, indicating normal cognitive function (Nasreddine et al., 2005).

It was a requirement that participants should not use hearing aids, but other than this no selection was made on the basis of hearing ability. Audiometric data for all participants are shown in Figure 6.1. Normal hearing is usually considered to be anything up to 20 dB hearing loss. The figure shows that this group of participants had good hearing, despite their age, with some mild hearing loss evident for a few participants in addition to the high frequency (8 kHz) loss that is very common in this age group.

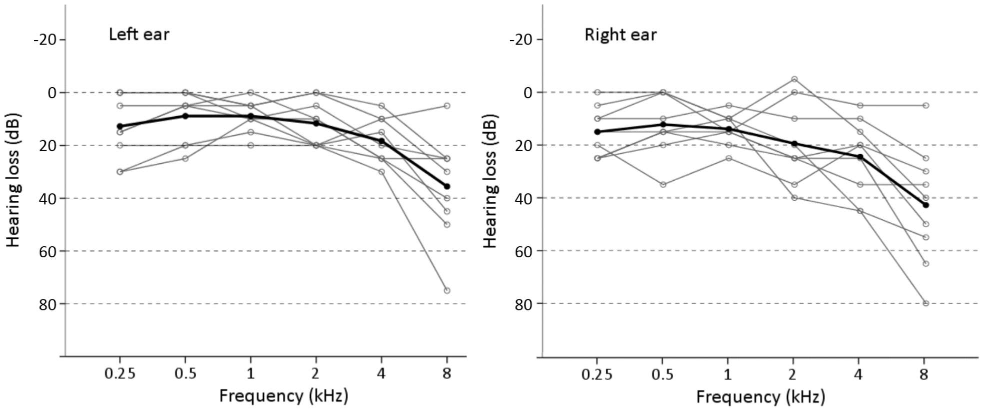


Figure 6.1: Audiometric data for all participants; the bold line indicates the mean

6.2.2.2 *Protocol*

The study protocol included a control period prior to training so that participants would act as their own controls. The protocol is shown in Figure 6.2. Participants were tested four times: a comprehensive baseline assessment was completed at T0, and a shorter battery was completed on three subsequent occasions (T1, T2 and T3).

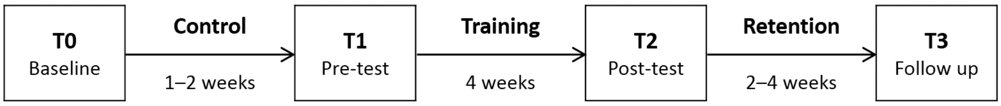


Figure 6.2: Training study protocol used in Experiment 6

6.2.2.3 *Testing procedures*

All testing took place in a sound-attenuated booth, and auditory stimuli were presented diotically through Sennheiser HD-25 headphones. The order of the initial baseline test battery is shown in Table 6.1 and the shorter battery used in subsequent testing is given in Table 6.2. Details of the individual test procedures are given below.

Table 6.1: Test battery for baseline assessment

	Task	Approximate duration (minutes)
1	Questionnaires	10
2	Audiometry	10
3	Cognitive assessment (MoCA)	10
4	Speech in noise: Practice	10
5	Speech in noise: Steady masker	15
6	IQ: WASI vocabulary subtest	10
	Break	15
7	Speech in noise: Modulated masker	15
8	IQ: WASI matrix reasoning subtest	10
9	Beat perception	15
		Total = 120

Table 6.2: Test battery for subsequent assessments

	Task	Approximate duration (minutes)
1	Speech in noise: Steady masker	15
2	Beat perception	15
3	Speech in noise: Modulated masker	15
		Total = 45

Questionnaires

Participants completed a background questionnaire which elicited information about their current levels of physical and musical activity, as well as any difficulties they experience with their hearing, e.g. listening to speech in noisy environments. Participants were asked to keep a diary of any musical activity throughout the study, and were instructed to continue with their normal routines throughout the control and retention periods.

The training subscale of the Goldsmiths' Musical Sophistication Index (Müllensiefen et al., 2011) was used as a measure of musical experience. The subscale consists of 9 questions which encompass both formal instrument training and informal musical experience (see Figure 2.1).

Cognitive tests

As mentioned above, the Montreal Cognitive Assessment (Nasreddine et al., 2005) was used to screen for mild cognitive impairment.

In addition, the vocabulary and matrix reasoning subtests of the Weschler Abbreviated Intelligence Scale (WASI; Wechsler, 1999) were used to obtain a measure of IQ.

Speech-in-noise perception

The UK Matrix Sentence Test (HörTech gGmbH, Oldenburg, Germany) was used to determine the speech reception threshold (SRT; the signal-to-noise ratio (SNR) that equated to 50% intelligibility). See Section 2.3.1.1 and Figure 2.2 for details of the stimuli and Section 3.2.2.2 for the procedure.

Two maskers were used: an unmodulated speech-spectrum noise (supplied with the test) and a sinusoidally amplitude-modulated version of the original noise (modulation frequency of 8 Hz; modulation depth of 80%). The noise signals were matched in overall intensity (root-mean-square level). Both of these maskers were found to have good sensitivity and reliability with the matrix test (see Section 3.2.2.3) which make them suitable for studying training effects.

At the start of the baseline testing session, participants completed a practice list with each masker to familiarise them with the stimuli and procedure and to allow for the substantial learning that usually takes place on first attempting the test (see Section 2.3.1.1). The results from these practice lists were not included in the analysis.

For each masker, participants completed a block of three test lists, which were used to obtain an average threshold.

Musical beat perception

The auditory-only subsection of the Beat Alignment Test (Iversen and Patel, 2008) was used to measure musical beat perception. See Section 3.2.2.2 for details of the stimuli and procedure. In addition to being asked to make a beat judgement for each excerpt, listeners were asked to rate how confident they were about their answer on a scale from 0 (guess) to 2 (certain). This was a feature of the original test (Iversen and Patel, 2008) and is included here as a second measure of beat ability since the sensitivity of the Beat Alignment Test to training effects is unknown. In addition, some of the young adults in Experiment 1 scored maximum marks on the test. If the same were to happen here, then there would certainly be no room for measurable training effects.

6.2.2.4 Training programme

The training programme ran for four weeks. Each week the whole group of participants attended a 2-hour workshop, led by a highly experienced Dalcroze teacher. The workshops took place in a large hall equipped with a piano. Activities focused on moving to the beat while the teacher improvised music on the piano. Participants were required to listen carefully and change their movements in response to changes in tempo or structure of the music or to predefined verbal instructions. Individual, pair and group tasks were included, and props such as balls were used for some exercises. For example, in one activity, participants had to bounce a ball in time with the music, but when the rhythmic pattern changed from a waltz to a march they had to switch to throwing the ball in time with the new beat, and vice versa.

Each workshop was recorded, and videos were provided to the participants so that they could practise a selection of the activities at home during the following week. Participants were asked to consolidate their learning by practising the homework activities (approximately 30 minutes) on three different days during the week. The videos were also used on the rare occasions when a participant had to miss a class through illness. In that case, the participant was asked to work through the whole of the class at home on their own, and then to practise the activities as normal. Participants were provided with a tennis ball for use during the homework activities.

One disadvantage of the training programme is that it was not possible to obtain objective measures for each participant's improvement on the trained tasks. The teacher's subjective assessment was that the group definitely improved throughout the four weeks. In place of a quantifiable measure of improvement on the trained tasks, the beat perception scores were used as proxy measures.

6.2.2.5 Analysis

A general note is required about the analysis used in this study. With only 9 participants, the analysis was underpowered. No corrections have been applied for multiple comparisons, and caution should be applied when interpreting the results. Limitations of the study and the analysis will be discussed below.

6.2.3 Results

6.2.3.1 Baseline assessment: time T0

The mean speech perception thresholds are shown in Figure 6.3 and in Table 6.3. The data from the young adults from Experiment 1 have been included for comparison. The figure shows that the older adults needed more favourable SNRs to achieve the same level of performance as the young adults. The older adults did benefit from modulation masking release, but to a lesser extent than the young adults who participated in Experiment 1. All group comparisons were significant (see Table 6.3).

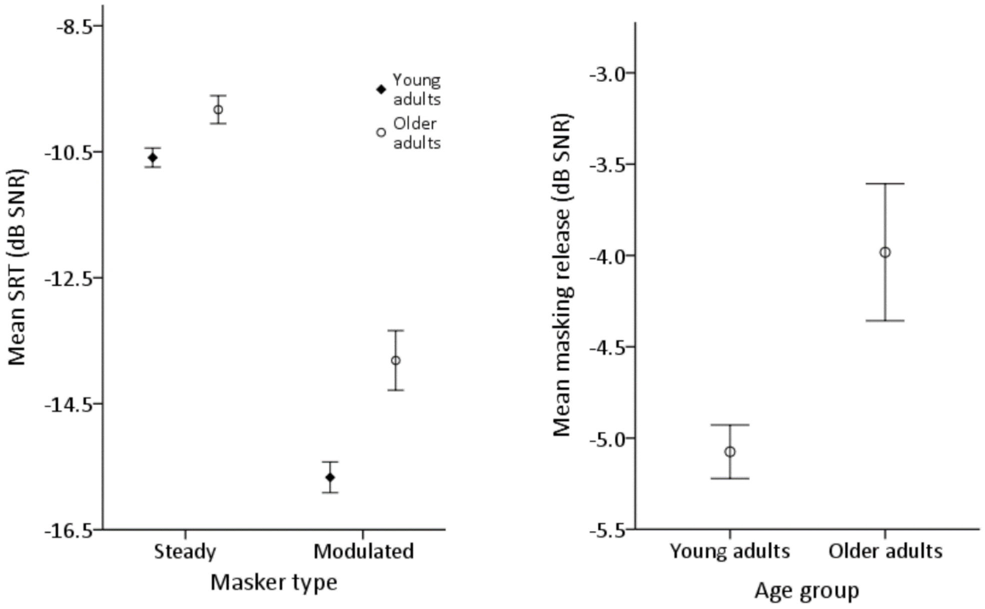


Figure 6.3: Means (and standard errors) for the baseline speech perception in noise measures, with the Experiment 1 data from young adults included for comparison

Table 6.3: Means (and standard deviations) for the baseline speech perception in noise measures, with the Experiment 1 data from young adults included for comparison

	Older adults	**Young adults**	**Independent *t*-test**
SRT in steady noise (dB SNR)	−9.8 (.71)	−10.6 (.73)	*t*(30) = 2.9, *p* = .007
SRT in modulated noise (dB SNR)	−13.8 (1.4)	−15.7 (1.2)	*t*(30) = 3.8, *p* = .001
Masking release (dB SNR)	−4.0 (1.0)	−5.1 (.70)	*t*(30) = 3.3, *p* = .003

Examination of scatter plots revealed that hearing ability (defined as the better-ear pure-tone average hearing loss) was correlated with the speech perception measures (see Figure 6.4). The Pearson correlation coefficients are given in Table 6.4. No other factors appeared to be associated with speech perception in noise at baseline. This is keeping with previous research that suggests that hearing ability is the primary predictor of speech perception in noise (Akeroyd, 2008).

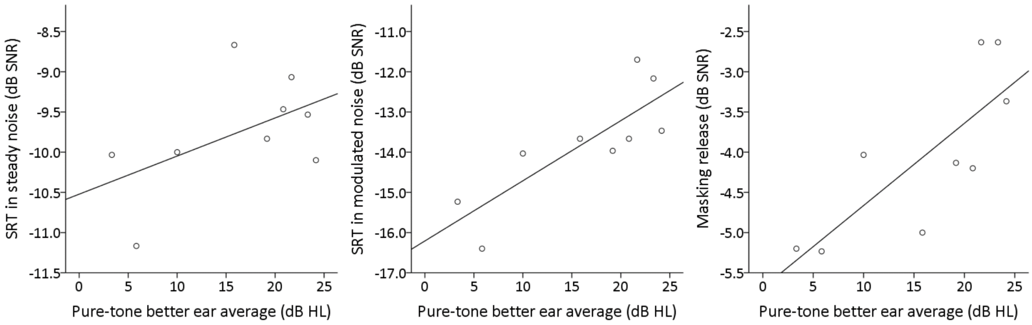


Figure 6.4: Scatter plots showing the relationships between hearing ability (measured in dB hearing loss (HL)) and speech reception thresholds (SRT) at baseline assessment; greater hearing loss was associated with worse speech thresholds and less masking release

Table 6.4: Pearson correlation coefficients for the relationships between hearing ability and speech perception in noise measures at baseline assessment

	Steady	Modulated	Release
PTA better ear	.52	.82**	.79**

*p<.05, **p<.01 (all one-tailed)

6.2.3.2 *Control period: T0 to T1*

The period following baseline assessment and prior to training was intended to act as a control period. No changes in SRTs were expected to occur during this time. The data in Figure 6.5 and Table 6.5 indicate that this was not entirely the case. While the SRT in steady noise remained stable, the SRT in modulated noise improved and there was a corresponding increase in masking release.

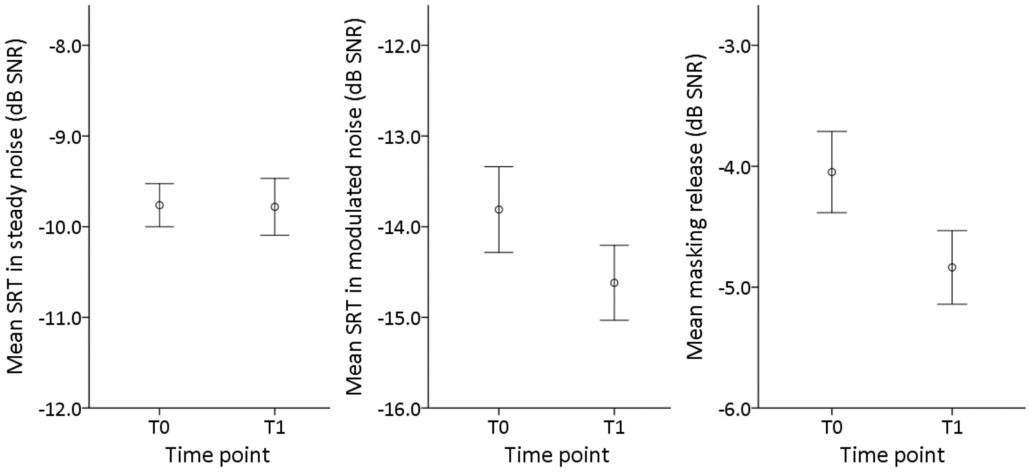


Figure 6.5: Means (and standard errors) for the changes in speech reception thresholds (SRT) during the control period (from baseline at time T0 to time T1)

Table 6.5: Changes in the means (and standard deviations) of the key variables during the control period: from time T0 to time T1

	T0	**T1**	**Paired *t*-test**
SRT in steady noise (dB SNR)	−9.8 (.71)	−9.8 (.94)	*t*(8) = −.09, *p* = .93
SRT in modulated noise (dB SNR)	−13.8 (1.4)	−14.6 (1.2)	*t*(8) = −3.6, *p* = .007
Masking release (dB SNR)	−4.0 (1.0)	−4.8 (.91)	*t*(8) = −3.6, *p* = .007
Beat perception (out of 36)	30.0 (5.0)	30.6 (4.2)	*t*(8) = .43, *p* = .68
Beat confidence (scale 0 to 2)	1.46 (.44)	1.37 (.39)	*t*(8) = −.91, *p* = .39

The improvement for speech in modulated noise was unexpected given the previous finding that this test had good test-retest reliability on repeated measures (see Section 3.2.2.3). Previous investigations of the matrix test suggest that, although learning does initially occur as participants become familiar with the stimuli, with the procedure used here the threshold should stabilise after a couple of practice lists (Hewitt, 2008). Participants completed four lists in the baseline session, so further learning was not expected to occur. The findings with the matrix test were not verified across multiple sessions, but another study using sentences in noise showed that there were no learning effects across five sessions for either steady or modulated noise (Stuart and Butler, 2014).

These findings do not preclude the possibility that the particular participants in this study did improve from one session to the next. Perhaps the gap between sessions gave them time to consider strategies for the test. However, there is another possible explanation which is worth considering.

In designing the test battery, it was desirable to alternate between different types of task in order to stave off boredom and tiredness during the long baseline assessment. For the subsequent testing sessions, a similar approach was employed but, with only three tasks to do, this meant completing the beat perception test directly before the speech test in modulated noise, whereas previously it had been done at the end.

It is possible that focusing on musical beat perception for 15 minutes prior to completing the speech task could have improved performance on the task, via temporarily strengthened temporal orienting. This idea is supported by examination of Figure 6.6. At the baseline assessment (T0), there was no discernible relationship between beat perception and masking release. However, at time T1, when the modulated noise condition had a proposed boost related to beat perception, the amount of masking release (which is the difference between the 'boosted' modulated SRT and the 'unboosted' steady SRT) was strongly correlated with beat perception ($r = -.85$, $p = .002$). In fact, beat perception and hearing ability together explained 95% of the variance in masking release (see Table 6.6).

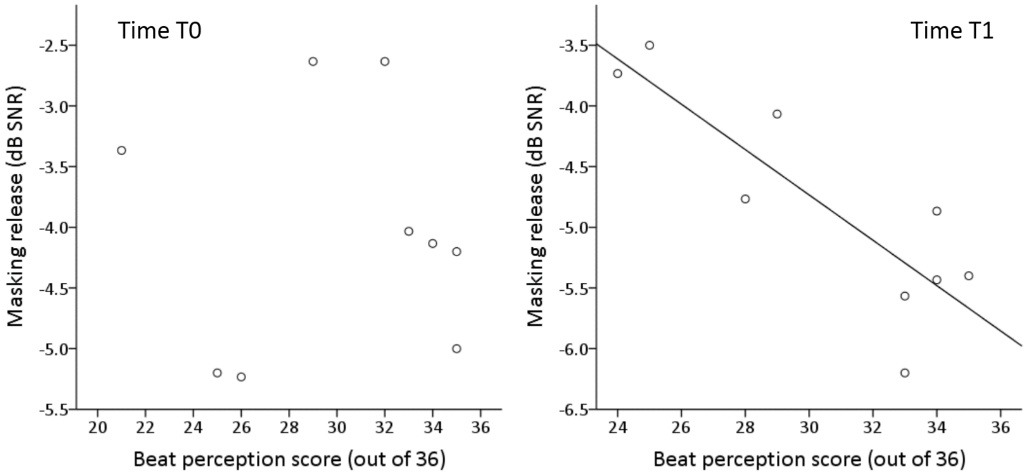


Figure 6.6: Scatter plots of beat perception and masking release at time T0 and time T1

Table 6.6: Linear regression model for masking release

Outcome measure and model	Predictors	β	*p*
Masking release	Hearing ability	.52	.001
$R^2 = .95$, $F(2,6) = 76.1$, $p < .001$	Beat perception	–.68	<.001

The finding that prior exposure and attention to a beat perception task could enhance subsequent speech perception in noise is a valuable result in its own right and will be discussed further in Chapter 7. However, for the purposes of the current study, it means that the baseline measure of SRT in modulated noise (and masking release) cannot reliably be used in comparison with subsequent measures, and there is therefore no true control period for these outcomes.

6.2.3.3 Training period: T1 to T2

Changes in the key variables over the training period are displayed in Figure 6.7 and Table 6.7. The most promising result is the SRT in modulated noise which was significantly improved at the post-test (T2) compared to the pre-test (T1): $t(8) = 1.97$, $p = .043$, effect size $r = .57$. The mean improvement was 0.53 dB, which is equivalent to an increase in intelligibility of about 6% (based on the reference slope data for the matrix sentence test (Hewitt, 2008)).

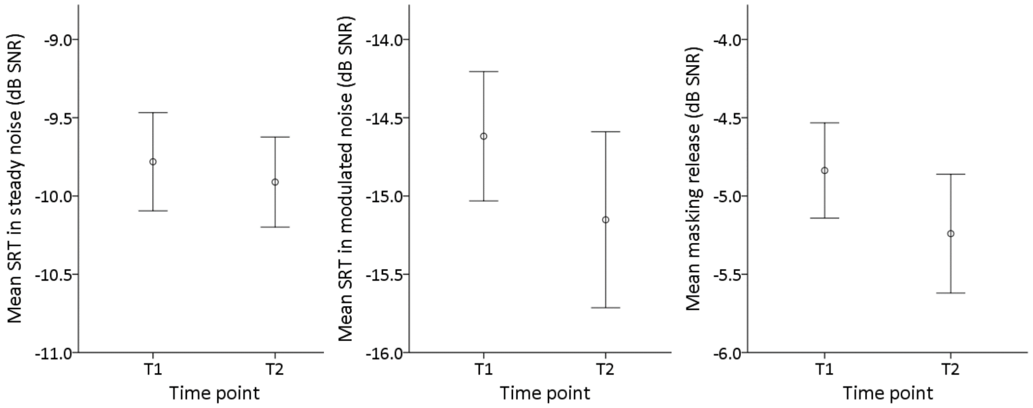


Figure 6.7: Means (and standard errors) for the changes in speech perception thresholds during the training period (from pre-test at time T1 to post-test at time T2)

Table 6.7: Changes in the means (and standard deviations) of the key variables during the training period: from time T1 to time T2; all *p*-values are one-tailed since all variables were expected to improve during training

	T1	**T2**	**Paired *t*-test**
SRT in steady noise (dB SNR)	−9.8 (.94)	−9.9 (.86)	*t*(8) = −.83, *p* = .22
SRT in modulated noise (dB SNR)	−14.6 (1.2)	−15.2 (1.7)	*t*(8) = −2.0, *p* = .043
Masking release (dB SNR)	−4.8 (.91)	−5.2 (1.1)	*t*(8) = −1.4, *p* = .11
Beat perception (out of 36)	30.6 (4.2)	31.2 (4.4)	*t*(8) = 1.2, *p* = .14
Beat confidence (scale 0 to 2)	1.37 (.39)	1.48 (.42)	*t*(8) = .95, *p* = .19

As discussed in Section 6.2.2.4, there were no objective measurements for improvement on the trained tasks. The beat measures (total score and confidence rating) were used as proxy measures, as the intention of the training was to improve beat perception. Neither of the beat scores showed significant improvement over the training period, although both show a small trend in the expected direction.

To investigate how changes in the speech measures might be linked to training, relationships between the outcome measures (SRTs in steady and modulated noise) and the skills targeted during training (beat perception and beat confidence) were explored (see Figure 6.8 and Table 6.8). The pattern of results for masking release was very similar to that for SRT in modulated noise, so masking release has not been included here.

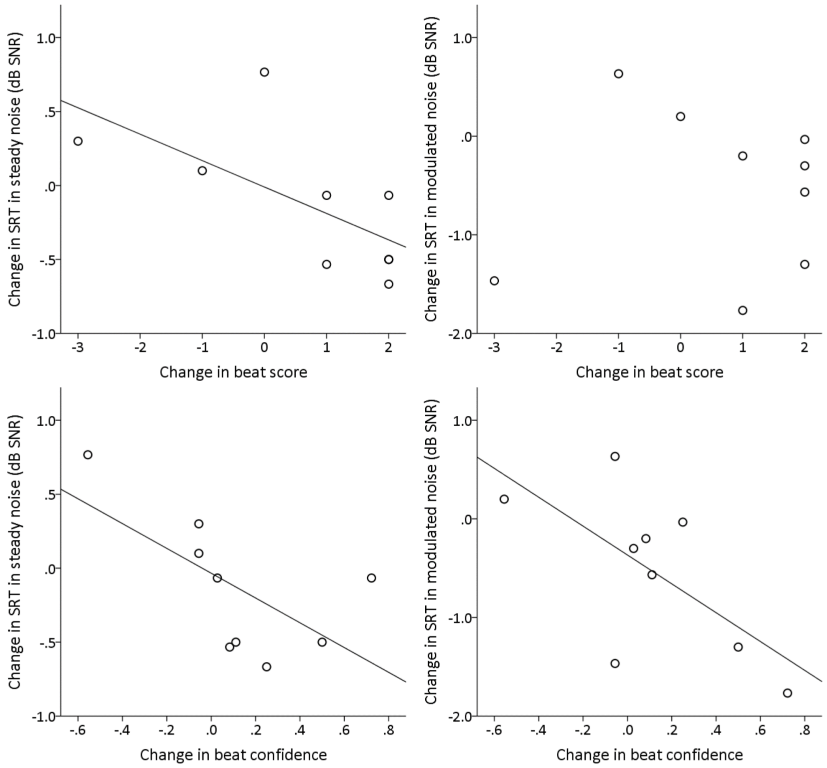


Figure 6.8: Scatter plots showing the relationships between outcome measures (SRTs) and trained skills (beat score and confidence rating)

Table 6.8: Pearson correlation coefficients for the relationships between outcome measures and trained skills

	Change in steady SRT	**Change in modulated SRT**
Change in beat score	−.66*	.05
Change in beat confidence	−.65*	−.65*

*$p<.05$, **$p<.01$; all one-tailed

Changes in outcome measures appear to be linked to changes in trained skills. An issue with relying on improvements in the beat perception score is that some participants scored highly at the baseline assessment and consequently did not have much room for improvement. This variable is therefore subject to ceiling effects and is not normally distributed. As a precaution, Spearman correlations were also checked and the pattern of results was identical.

The beat confidence rating was included for exactly this reason – as an alternative measure of whether training was enhancing some measure of beat perception. The fact that improvements in this measure are associated with improvements in SRTs is encouraging.

Finally, associations between changes in SRTs and baseline performance were investigated (see Figure 6.9 and Table 6.9). The baseline (T0) measures were used instead of the pre-test (T1) measures to avoid the confound of correlating (T2 – T1) with T1. For speech in modulated noise, improvements in SRT were correlated with baseline performance for speech in steady noise and for the beat perception test.

The worse the baseline measure of beat perception, the greater the improvement for speech perception in modulated noise. If the improvement in SRT is indeed mediated by training-related improvements in beat perception (as suggested by the increase in beat confidence), then this finding fits with the perceptual learning literature. It is commonly reported that the magnitude of training improvement is inversely proportional to the baseline performance, i.e., the worse the initial performance, the more room for improvement and the faster the learning (e.g., Astle et al., 2013; Fahle and Henke-Fahle, 1996). On this premise, poor initial beat perception could have led to greater training improvement for beat perception, which may then have transferred to speech perception in modulated noise as hypothesised.

Conversely, the better the baseline measure of SRT in steady noise, the greater the improvement for SRT in modulated noise. This appears to disagree with findings from perceptual learning, although the two speech tasks do not measure exactly the same skills. Speech perception in steady noise is mainly a task of perceptually separating the speech from the background, whereas listening in modulated noise additionally engages other factors such as working memory to listen in the dips (see Section 1.4.2). The skills required for speech perception in steady noise could be considered as a subset of the skills needed for speech perception in modulated noise. Perhaps, then, a certain level of performance in steady noise is required in order for training benefits to be observed for the more complex modulated noise condition.

Baseline SRT in steady noise and training improvement in beat confidence account for 88% of the improvement for SRT in modulated noise (see Table 6.10).

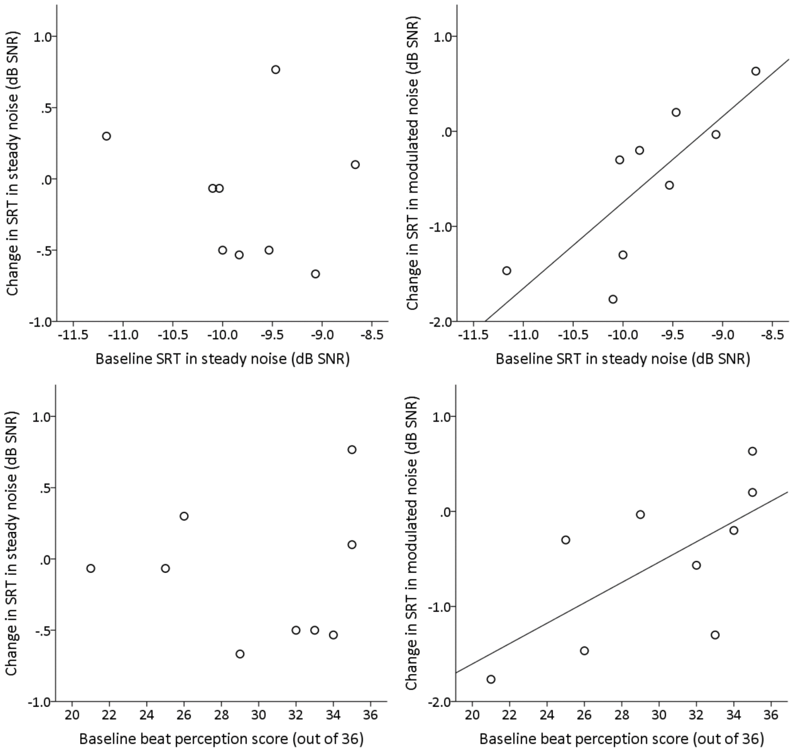


Figure 6.9: Scatter plots showing the relationship between changes in thresholds during the training period and baseline performance

Table 6.9: Pearson correlation coefficients for the relationships between training-related changes

	Change in steady SRT	Change in modulated SRT
Baseline steady SRT	−.17	.79**
Baseline modulated SRT	−.49	.33
Baseline beat score	.01	.66*

*p<.05, **p<.01; all one-tailed

Table 6.10: Regression model for the improvement in speech perception in modulated noise

Outcome measure and model	Predictors	β	p
Change in modulated SRT	Baseline steady SRT	.71	.001
R^2=.88, F(2,6)=30.6, p = .001	Change in beat confidence	−.54	.005

6.2.3.4 Retention period: T2 to T3

Changes during the post-training retention period are given in Figure 6.10 and Table 6.11. Although the changes are not statistically significant, there are some interesting patterns. Masking release and SRT in modulated noise (which had shown improvement during training) show a declining trend, as do the beat measures (although training improvements in these were small and non-significant). This is what might be expected if the training programme was insufficient to cause lasting changes, i.e., improvements have not been retained. Although this could be interpreted as a negative result, since retention is an important part of any training, it also suggests that the improvements in these outcomes were in fact due to training. If that is the case, then perhaps a longer training programme could lead to lasting improvements.

On the other hand, SRT in steady noise continued on a trend towards improvement, possible indicative of delayed transfer of training to this skill. Although this improvement did not reach significance, when the overall change (from time T1 to T3) in SRT for steady noise is considered, the result is a significant improvement ($t(8) = 2.0$, $p = .043$). The mean improvement was 0.37 dB SNR, which is equivalent to a performance benefit of about 4%.

Table 6.11: Changes in the means (and standard deviations) of the key variables during the retention period: from time T2 to time T3

	T2	**T3**	**Paired *t*-test**
SRT in steady noise (dB SNR)	−9.9 (.86)	−10.2 (.75)	*t*(8) = −1.8, *p* = .11
SRT in modulated noise (dB SNR)	−15.2 (1.7)	−14.9 (1.5)	*t*(8) = 1.5, *p* = .18
Masking release (dB SNR)	−5.2 (1.1)	−4.7 (1.0)	*t*(8) = 2.3, *p* = .051
Beat perception (out of 36)	31.2 (4.4)	30.1 (4.1)	*t*(8) = −1.0, *p* = .35
Beat confidence (scale 0 to 2)	1.48 (.42)	1.39 (.40)	*t*(8) = −2.2, *p* = .063

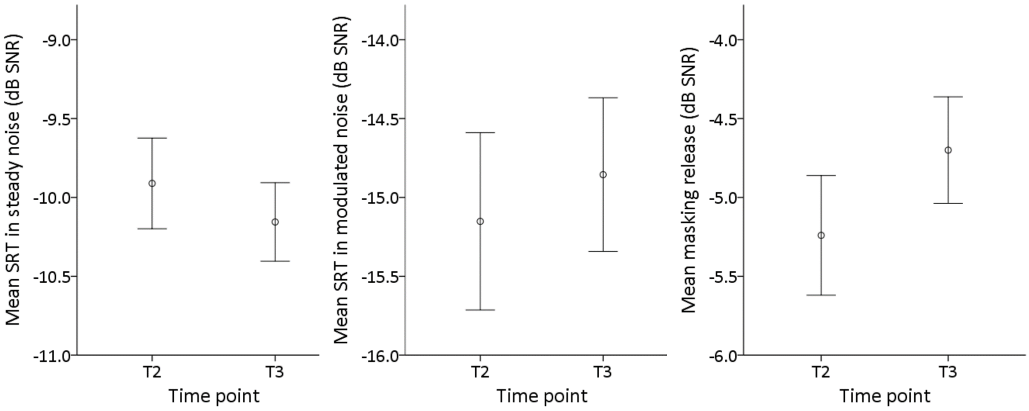


Figure 6.10: Means (and standard errors) of the changes in speech perception thresholds during the retention period (from T2 to T3)

6.2.3.5 *Summary: T0 to T3*

The speech perception in noise data for this study are summarised in Figures 6.11 and 6.12.

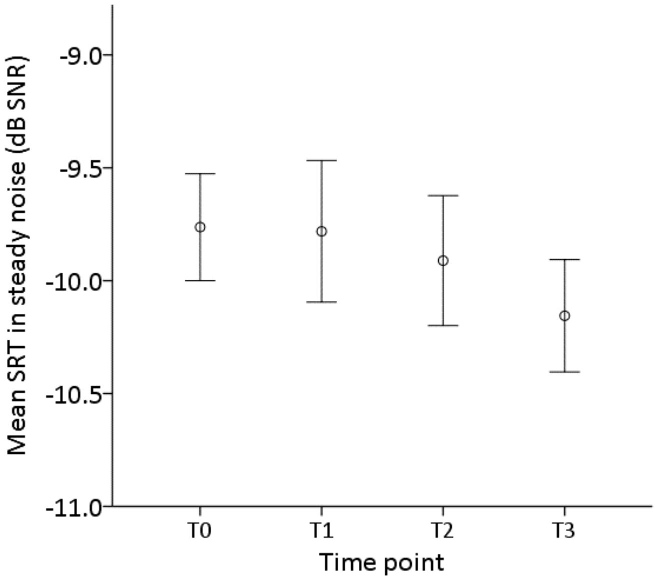


Figure 6.11: Means (and standard errors) for measures of the SRT in steady noise throughout the study; training was administered between T1 and T2

For speech in steady noise, there was no change during the control period (T0 to T1) as expected. During and after the training programme, there was a trend towards improving SRT in steady noise. The greatest improvement for SRT in steady noise was between T1 and T3. This improvement was significant and was equal to 0.37 dB SNR. Comparison of the change in

SRT for steady noise over this time period compared to the control period did not reach significance ($t(8) = 1.0, p = .16$).

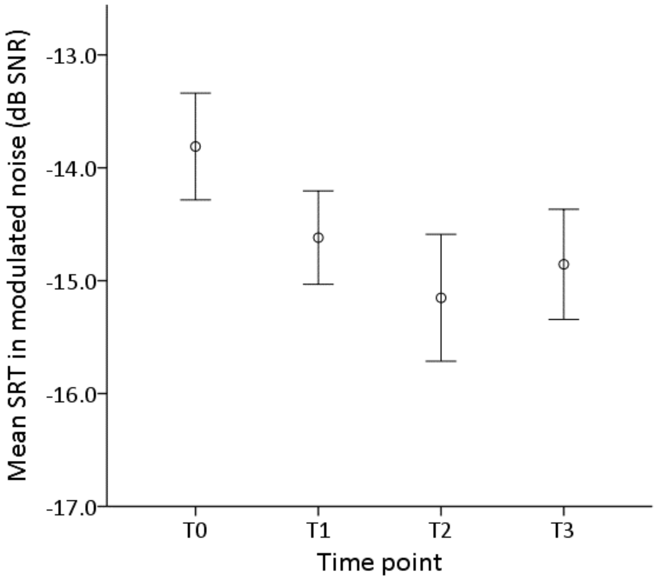


Figure 6.12: Means (and standard errors) for measures of the SRT in modulated noise throughout the study; training was administered between T1 and T2

For speech in modulated noise, there was significant improvement during what was intended to be the control period. As discussed above, this may have been due to the different testing order used at each time point rather than a true reflection of change in performance. There was a significant improvement in SRT for modulated noise during the training period (equal to 0.53 dB SNR), but performance declined during the retention period.

Due to the issue with the control period and the general lack of power in this study, a final analysis was performed to examine individual improvements based on a confidence interval approach. Using the pre-test data from time T1, the intra-individual standard deviation for the two SRTs was derived from the one-way ANOVA (with subject as the factor): root mean square error divided by $\sqrt{3}$ (as an average of three values was used). The intra-individual standard deviations were 0.33 and 0.49 for SRT in steady and modulated noise respectively. These values were used to create 95% confidence intervals ($\pm 1.96 \times$s.d.) around each participant's pre-test SRTs at time T1. These confidence intervals are displayed in Figures 6.13 and 6.14. In each figure, the solid line represents identical scores at both time points, and the dotted lines are the confidence intervals: a data point lying below the bottom dotted line indicates significant improvement for that participant.

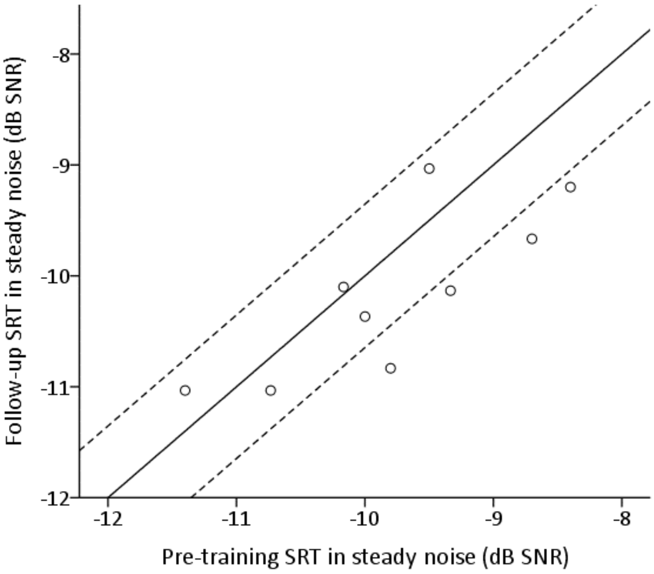


Figure 6.13: Scatter plot of individual SRTs in steady noise measured pre-training (time T1) and at the follow-up test (time T3); the solid line represents identical scores, while the dotted lines represent confidence intervals; points below the bottom dotted line indicate significant improvement

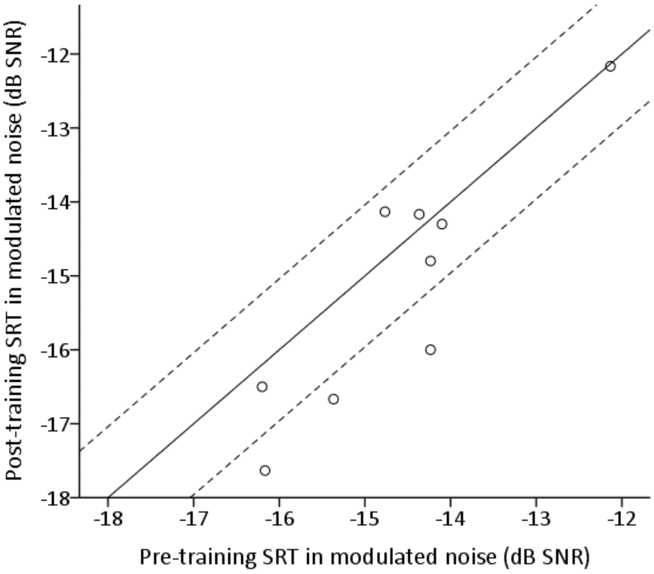


Figure 6.14: Scatter plot of individual SRTs in modulate noise measured pre-training (time T1) and post-training (time T2); the solid line represents identical scores, while the dotted lines represent confidence intervals; points below the bottom dotted line indicate significant improvement

Based on the confidence interval approach, four participants displayed significant improvement for speech perception in steady noise (from T1 to T3) and three participants displayed significant improvement for speech perception in modulated noise (from T1 to T2). The current data is insufficient to explain why these particular individuals might have been predisposed to benefit from the training, or if others would benefit given more time. However, for some individuals it is possible to offer an explanation. For example, one participant who showed no benefits of training had in fact been a dancer throughout her life, and had therefore no doubt had copious prior experience moving to the beat of music.

6.3 Discussion

Experiment 6 aimed to evaluate a musical beat training programme in terms of its impact on speech perception in noise for older adults. Overall, the results are promising, but caution should be exercised when interpreting these results as the study had considerable limitations. The small sample size, lack of an active control, and lack of measurable outcomes of the trained activities should all be taken into account. Further studies will be needed to confirm the findings reported here.

The Dalcroze workshops were successful in creating an engaging musical atmosphere, and all participants who started the training went on to complete the study. Feedback from the participants confirmed that they enjoyed the workshops, and particularly liked the social aspect of coming together once a week to share the experience. The homework activities were not so successful, perhaps because it was not possible to recreate the enjoyable social atmosphere at home. Participants did their best to complete the activities, and record these on their diary sheets, but feedback suggested that they did not enjoy this part of the training as much. The homework activities were included in an attempt to make the training quite intensive over a short period. Future studies should consider using either more frequent workshops or a longer training period or both, to explore the timeframe of any improvements.

In terms of speech perception in noise, there were modest significant improvements in threshold for modulated noise immediately after training and for steady noise after a prolonged period. However, the lack of an active control (or indeed any reliable control for the modulated noise condition) means that caution should be exercised when interpreting these results. Further research is needed to investigate the timecourse of any improvements and to see if a longer training programme will lead to lasting benefits, and whether the size of improvement would be meaningful to a patient (McShefferty et al., 2016).

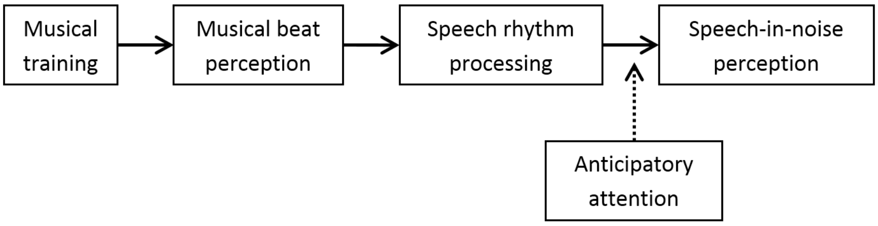
Dalcroze methods place demands on auditory, motor and cognitive systems. The aim of this study was to target beat perception to see if this would transfer to speech in noise perception. However, it is also possible that any observed benefits were due to cognitive improvements brought about by the multitask practice included in the training. The fact that improvements in speech thresholds were associated with improvements in beat confidence suggests that beat perception does play a part. Future studies should incorporate additional measures of cognitive function and beat perception. These should be sensitive to training improvements with no ceiling effect in order to elucidate the likely nature of transfer.

Further work is also needed to explore the effect of individual differences on potential benefits of training. It is not necessarily the case that one training regimen will work for every individual. Some factors to consider include: musical experience, dance experience, personality and personal preference (i.e., do they like music?).

An accidental discovery in this study also indicates further new avenues for research. Results from the control period suggest that performing the beat perception test prior to the speech test (in modulated noise) may have primed the mechnism by which attention is oriented in line with temporal predictions and therefore improved the speech reception threshold. This possibility will be discussed in more detail in Chapter 7.

CHAPTER 7

General discussion



The ultimate goal of the research presented in this thesis was to investigate whether short-term musical training could improve speech perception in background noise. This goal was broken down into three separate research questions which were investigated in turn. This chapter presents a summary and discussion of the main findings and limitations of the current research, and proposes possible directions for future research.

7.1 Question 1: Are specific musical skills associated with speech perception in noise?

In Chapter 3, a correlational design was used to explore the relationships between musical skills and speech perception in noise. To avoid the confounds associated with testing highly trained musicians, this study recruited a sample from the general population, who therefore had a range of musical backgrounds. The analysis revealed that musical beat perception was strongly associated with all of the speech perception measures, even when controlling for potentially confounding factors (working memory and frequency discrimination).

Beat perception was therefore identified as a possible link between musical training and speech perception in noise and became the focus of subsequent research presented in this thesis.

7.1.1 Why might musical beat training transfer to speech perception?

The issue of *how* beat perception might contribute to speech perception in noise was the second topic of investigation in this thesis and will be discussed below. This section considers the question of *why* transfer may occur, with reference to the proposals introduced in Section 1.1.3.

7.1.1.1 Common processing

If the same skill is used in both music and speech perception, then it follows that improving this skill in one domain should improve it in the other (Besson et al., 2011). This begs the question: is beat perception used in speech perception as it is in music?

While music contains an isochronous beat around which rhythms are based, regularity in speech is created by the metric structure of stressed and unstressed syllables. So the ‘beat’ in speech refers to the quasi-regular pattern of stressed syllables.

Musical beat perception can be demonstrated by synchronising movements with the beat; for example, by dancing, clapping along with a musical performance, or – more commonly in laboratory settings – tapping a finger (e.g., Drake et al., 2000). Lidji et al. (2011) found that listeners can entrain finger taps to speech meter in a similar way, suggesting a shared process between music and speech.

It has also been shown that musicians are more sensitive to speech meter (Marie et al., 2011), which adds further support for the idea of a link between beat processing in music and speech.

7.1.1.2 Working memory as a mediating factor

Kraus et al. (2012) proposed that working memory is the key factor in the transferral of learning from music to speech.

In Experiment 1, performance on the Beat Alignment Test was linked with digit span scores. This could be a consequence of the task design which requires beat predictions to be held and updated in working memory ready to be compared to the timing of superimposed beeps. In fact, partial correlations between beat perception and speech reception thresholds remained strong even when controlling for working memory. These findings suggest that working memory was not involved in mediating the observed link between beat perception and speech perception in noise.

Listening to music often results in spontaneous movement to the beat, suggesting that beat perception happens automatically and without cognitive effort. The current hypothesis that beat perception provides a link between musical training and speech perception in noise is not, therefore, compatible with the working memory proposal put forward by Kraus et al. (2012).

7.1.1.3 The OPERA hypothesis

The OPERA hypothesis (Patel, 2014) suggests that musical training can enhance speech perception via any sensory or cognitive process that is common to both domains, as long as certain conditions are met. Namely that the brain networks for speech and music processing overlap, that music places greater demands on the process than does speech, and that music engages the process with emotion, repetition and attention.

> **O**verlap – Musical beat perception is known to recruit motor areas of the brain, including the basal ganglia (Grahn and Brett, 2007; Grahn and Rowe, 2012). Patients with Parkinson's disease – which affects the basal ganglia – display deficits in beat-based musical rhythm perception (Grahn and Brett, 2009) as well as in the processing of speech rate (Breitenstein et al., 2001). Furthermore, patients with lesions in the basal ganglia have impaired speech meter perception (Kotz and Schmidt-Kassow, 2015). Together these findings suggest that the basal ganglia could be part of an overlapping network for beat processing in music and speech, thereby satisfying the first criterion.
>
> **P**recision – Regular meter is useful for speech perception, but beat perception is crucial for successful musical performance. An audience is unlikely to appreciate musicians who cannot play in time with each other. Synchronisation of playing in time with music must be preceded by precise perception of the beat. It is logical therefore that musical training would demand a higher precision of beat processing than is required for everyday speech perception.

> **E**motion – Moving to a beat is a key part of enjoyable social activities such as music-making and dancing. It is easy to imagine that practising synchronising with music, particularly if it also involves entraining movements with other people, could elicit the positive emotion necessary for this criterion to be fulfilled.
>
> **R**epetition – Musical beat training will inevitably involve repeated practise of entraining to a beat.
>
> **A**ttention – In the previous section, it was noted that beat perception happens spontaneously and without cognitive control. While it is not necessary to orient attention towards the temporal structure of music in order to perceive a beat, it is possible to focus attention on the beat and this will be necessary in order to improve synchronisation abilities during training.

In conclusion, with an appropriately designed programme, training in musical beat perception could satisfy all of the criteria of the OPERA hypothesis. This supports the idea that training in musical beat perception could result in transfer of learning to speech perception.

7.1.2 Consideration of other musical skills

The aim of Experiment 1 was to identfy musical skills which are associated with speech perception in noise. Musical beat perception appears to be one such skill, but it is not necessarily the only one. Further work in this area might consider other musical skills which were not tested here, or indeed different tests for melody and rhythm perception.

The Musical Ear Test uses a same/different paradigm which is common amongst musical aptitude tests (e.g., Gordon's Advanced Measures of Musical Audiation – AMMA; GIA Publications, Inc., Chicago, IL, USA). This design is by its nature heavily dependent on working memory. Memory for melodies and memory for rhythms are no doubt important skills for musicianship, but in Experiment 1 the working memory confound made it unclear whether rhythm skills are linked to speech perception in noise or if the observed correlation was purely due to working memory. This could be addressed by using alternative measures for melody and rhythm perception which require a perceptual judgement of a sequence rather than a same/different comparison. For example, categorising pitch contours, as these are important for speech perception (Miller et al., 2010).

There are other aspects of musical ability that were not considered for Experiment 1, but which could potentially be linked to speech perception in noise. For example, recognising timbres of different instruments could be linked to recognising – and selectively attending to – different voices. Similarly, harmony skills could be linked to auditory scene analysis, since harmonic components can be used to separate sound sources (see Section 1.2.2).

Both of these skills could be predicted to help in separating a target voice from competing speech. However, it is unlikely that correlations would have been observed for the noise maskers used in Experiment 1, since this task did not involve separation of multiple voices or harmonic sounds. A further study would be needed to examine the relationships between timbre and harmony skills and speech perception with speech maskers.

7.1.3 Interpreting differences in speech reception thresholds

The Matrix Sentence Test was used to assess speech perception in steady and modulated noise maskers. For the young adults who participated in Experiment 1, the range of measured thresholds spanned 3.1 dB for steady noise and 4.4 dB for modulated noise. Comparable ranges were found for the older adults in Experiment 6, although the absolute thresholds were significantly worse than for the young adults. Combining the data from the two groups results in ranges of 3.2 dB and 5.9 dB for steady and modulated maskers respectively.

The just-noticeable difference in signal-to-noise ratio for speech in steady noise has been reported to be 3 dB (McShefferty et al., 2015). This suggests that, for the participants tested here, the thresholds for the very best and very worst performers should only just be distinguishable from each other. It is important to note that none of the participants reported having any particular difficulties understanding speech in background noise. This begs the question: do the measured differences in thresholds actually translate to meaningful differences in real world abilities?

It could, however, be argued that such a question is not appropriate given the myriad differences between the two situations. In the lab, participants were wearing headphones and were focused on the task at hand; stimuli were carefully controlled; masking noise was consistent throughout; the test was repetitive, allowing familiarisation with the task and stimuli; target words were drawn from a finite number of options; and attention was only required in short bursts, i.e., the length of a sentence.

In the real world, it is much more likely that listeners will need to: following an ongoing conversation for a prolonged period of time; try to ignore multiple dynamic sound sources, often including competing speech; repeatedly switch focus between different talkers and other demands on their attention; and piece together the speech signal without the benefit of advance information about the content or frequent opportunities to pause and work out what was said.

Given the varied and changeable nature of everyday listening environments, objective tests of speech perception in noise with controlled stimuli are necessary and provide insight into auditory perception, even if the thresholds do not directly relate to listeners' subjective experiences in the real world.

7.1.4 Beat perception in specific populations

The participants in Experiment 1 had a range of musical backgrounds, but they were all young adults with normal hearing. It would be interesting to see if the link between beat perception and speech perception in noise persists in other populations.

7.1.4.1 Clinical populations

To better understand the relationship between beat perception and speech perception in noise, it would be useful to test these skills in clinical populations that are known to have poor speech perception in noise.

For example, children with language disorders often struggle with speech perception in noise (e.g., Ziegler et al., 2009) and have also been reported to have difficulty with musical beat tasks (Corriveau and Goswami, 2009; Muneaux et al., 2004). However, as these tasks were not tested within the same group of children, it is impossible to deduce the nature of any association between the two skills.

This idea partially motivated the recruitment of older adults for the training study in Chapter 6. However, despite the advanced age of some of the participants, the levels of hearing ability among the group were actually very good. Despite performing worse on the matrix sentence test than the young adults in Experiment 1, the older adults reported no particular difficulty with speech perception in noise in their everyday lives. This was unexpected given prior research (see Section 1.6.2).

Some of the training participants also had excellent musical beat perception at the start of the study, which meant they were less likely to benefit from the beat training as they had little capacity for improvement (Astle et al., 2013; Fahle and Henke-Fahle, 1996).

An alternative approach would be to study a population who are known to have impaired musical beat perception and assess their ability to perceive speech in background noise. For example, Parkinson's disease affects the basal ganglia – an area of the brain which is involved in beat perception (Grahn and Brett, 2009) and has also been proposed to be involved in forming temporal predictions during speech perception (Kotz et al., 2009). Patients with Parkinson's disease have been shown to have difficulty discriminating beat-based rhythms (Grahn and Brett, 2009), so it would be interesting to see if they also have deficits for speech perception in noise.

7.1.4.2 Non-native speakers of English

Another population who have difficulties with speech perception in noise are non-native speakers of the language (e.g., Mayo et al., 1997; van Wijngaarden et al., 2002). Given the evidence that instrumental music reflects the spoken prosodic rhythms of the language of the composer (Patel and Daniele, 2000), perhaps musical beat training could be used to help non-native speakers of English.

Lidji et al. (2011) found that both English and French speakers could tap along to the meter of English and French utterances. However, tapping to English utterances was more regular than to French utterances because of the stress-based rhythm in English that does not occur in French. Furthermore, English speakers tapped more regularly than French speakers and were more likely to pick out the underlying 'beat' rather than tapping along with the syllables. Lidji et al. (2011) suggested that the English speakers' long-term experience with the language allowed them to entrain to the meter of the English utterances to a level that French speakers could not.

Perhaps non-native speakers' non-familiarity with the rhythmic structure of English could at least partially explain their difficulties with speech perception in noise. Non-native speakers might therefore benefit from training in beat perception using English music or indeed a combination of music and speech rhythm tasks, in order to become more familiar with the stress-based metric structure of the English language.

7.2 Question 2: How might beat perception contribute to speech perception in noise?

To do well in the beat perception test, it is necessary for the listener to form predictions about when the next beat will occur in order to judge if a superimposed beep arrives at the same time. This reasoning led to the hypothesis that beat perception could enhance speech perception in noise via orienting of attention to points in time when a target is predicted to occur.

In Experiment 2, priming with an isochronous sequence was shown to enhance detection of pure-tone targets in noise and perception of monosyllabic words in noise. Thresholds for targets which occurred at expected times (on the beat) were significantly better than for targets which were displaced in time. More complex rhythms were used in Experiment 3, and it was shown that when the beat of the priming sequence was less salient, and therefore required some musical expertise to perceive, the magnitude of the priming effect for tone detection was associated with musical beat perception.

Returning to the initial focus of speech perception in noise, Experiment 5 used a sentence context to show that rhythmic priming can be driven by speech meter as well as by the musical rhythms used in Chapter 4. Thresholds for the final target word were better when the target occurred at its natural (and therefore predicted) point in time compared to when it was delayed.

Together, these findings support the hypothesis that beat perception may enhance speech perception in noise via rhythmic priming driven by the metric structure of speech.

7.2.1 Musical beat perception and rhythmic priming

The current research successfully demonstrated that rhythmic priming can enhance the perception of targets in noise. The second assumption of the hypothesis – that this priming effect is modulated by beat perception – was shown for the duration beat rhythm primes in Experiment 3, but not for priming with speech meter. One encouraging piece of evidence is that musicians have an enhanced sensitivity to speech meter (Marie et al., 2011), but further research is needed to test if musical beat perception does in fact have an influence on rhythmic priming during speech listening.

The priming paradigm from Experiment 5 ('Ready Baron, go to red...') could be adapted to vary the colour which precedes the target number, using words of different lengths and/or stress patterns. To observe a priming benefit in this case, the temporal prediction for the target location would have to be adapted accordingly. If a few different possibilities are mixed within a block, then temporal predictions would have to be formed on a trial-by-trial basis. This would avoid the potential confound in Experiment 5, whereby the rhythmic pattern of the priming phrase was identical throughout the block.

Further research could use speech with more complex metrical structures to see if an association would emerge between beat perception and the priming effect. These adaptations might also reveal developmental differences during childhood, which were not evident for the 6–11 year-olds tested with the simple stimuli in Experiment 5.

7.2.2 Converging evidence from neuroscience

The research presented in this thesis adopted a purely behavioural approach. However, there is converging evidence from neuroscience that is worth considering. This section will present a brief description of some neuroscientific findings that support the hypothesis explored in this thesis.

7.2.2.1 Orienting of attention during music listening

Anticipatory attention effects have been reported during real music listening, with enhanced processing for probe sounds which coincided with the beat of the music (Bolger et al., 2013; Tierney and Kraus, 2013a). In addition, this enhancement was correlated with the ability to tap along to a beat (Tierney and Kraus, 2013a). This suggests a link between synchronisation to a simple beat and perception of the beat in real music.

In both of these studies (Bolger et al., 2013; Tierney and Kraus, 2013a), the musical excerpts (classical and pop respectively) were carefully chosen so that the beat was easily perceivable by all participants. Perhaps if a more complex musical piece – with a less salient beat – were used, then a correlation might be observed between rhythmic priming and beat perception. This would support the hypothesis that good beat perceivers have an enhanced mechanism for extracting implicit regularity in order to benefit from anticipatory attention.

7.2.2.2 Orientation of attention during speech listening

Behavioural evidence that attention is oriented towards stressed syllables when listening to speech was reviewed in Section 1.5.2.

There is also neuroscientific evidence that listeners employ temporal attention when listening to narrative speech. Astheimer and Sanders (2009) examined electrophysiological responses to attention probes which could either coincide with word onsets or occur at random control times during a continuous speech stream. Probes which occurred around the time of word onsets were found to elicit larger responses – indicative of greater allocation of attention – than probes which occurred at control times. The authors concluded that attention is oriented to word-initial segments when listening to narrative speech.

Together these findings support the concept of dynamic attending – oscillatory entrainment of anticipatory attention in response to rhythmic stimuli (Large and Jones, 1999) – and suggest that similar priming mechanisms are used for both music and speech listening.

7.2.2.3 Neural entrainment as a mechanism of selective attention

Dynamic attending theory (Large and Jones, 1999) is based upon the idea that internal oscillations entrain to external rhythmic stimuli in order to orient temporal attention, as described in Section 1.5.1.2. Oscillations are phase-locked so that peaks in neuronal excitability coincide with predicted onsets, thereby affording enhanced processing to stimuli which occur at predicted times.

When listening to speech, it has been shown that oscillations in the auditory cortex entrain to temporal envelope information, and that this phase-locking is enhanced when the speech is intelligible (Peelle and Davis, 2012). Furthermore, when there are two competing speech signals, phase-locking to the attended speech stream is stronger than that to the unattended stream (Horton et al., 2013). Phase-locking to the unattended speech was in the reverse direction, so that minimum excitability coincided with predicted onsets, suggestive of a suppression effect of entrainment on unattended stimuli (Horton et al., 2013).

In the rhythmic priming experiments in Chapters 4 and 5 a steady noise masker was chosen so as to minimise confounding temporal information. However, if entrainment to temporal regularity can enhance attended streams while also suppressing unattended streams, then perhaps a masker with temporal regularity (such as modulated noise or competing speech) would have resulted in greater benefits of rhythmic priming. By extension, as beat perception is hypothesised to enhance the entrainment mechanism, then greater modulatory effects of musical beat perception may have been observed.

Further research in this area could utilise combined methods to put the behavioural findings in a neuroscientific context. Power et al. (2012) developed a rhythmic priming paradigm that could be used to study individual differences in oscillatory entrainment. Such a paradigm could be useful for exploring the link between musical beat perception and rhythmic priming.

7.2.3 What is a meaningful difference in threshold?

In the studies presented in this thesis, differences in threshold due to attention or training have been reported in terms of the performance benefit (% correct) per 1 dB improvement in signal-to-noise ratio at threshold. For example, in Experiment 5, the benefit of priming for on-beat speech targets for the adult group was a 2.5 dB improvement in threshold. This was equivalent to an extra 15.1% of targets correctly identified. However, this figure only applies to signal-to-noise ratios in the region of the speech reception threshold (see Section 2.4.3). It is therefore difficult to interpret the results in terms of real world benefit, since this will vary for different listening environments.

The just-meaningful difference in signal-to-noise ratio – defined as the minimum improvement for which a patient would seek an intervention such as a hearing aid – was recently reported to be 6 dB (McShefferty et al., 2016). This is far greater than the benefits reported in the current research, but that doesn't necessarily mean that the results are not meaningful. The benefits reported here were for participants who did not report difficulties with speech perception in noise. Greater benefit may be observed for people who do struggle to understand speech in complex auditory environments.

7.2.4 Adaptations of the rhythmic priming paradigm

Rhythmic priming paradigms have typically measured benefits in terms of reaction times to targets in quiet (e.g., Cason and Schön, 2012; Quené et al., 2005). Having successfully demonstrated that rhythmic priming can also enhance perceptual thresholds for targets in noise, there are numerous potential avenues for future research.

7.2.4.1 Audibility of priming sequences

In the current paradigm, the priming sequences were always clearly audible above the noise, and only the level of the target varied. This choice was made to maximise the likelihood of observing rhythmic priming effects, but it came with a sacrifice in terms of ecological validity. If listening to speech in background noise, the whole speech stream will be masked to a similar degree.

The experiments could be repeated with the priming sequences matching the varying target level, but this would pose extra questions. How much of the speech prime would need to be heard in order to generate rhythmic priming? Does it need to be intelligible, or just loud enough so that cues to lexical stress can be identified?

Perhaps electrophysiological methods could be used for this purpose with attention probes like those used by Astheimer and Sanders (2009). The signal-to-noise ratio of the ongoing speech could be manipulated and attention probes used to determine for which levels rhythmic priming effects are observed.

The use of continuous speech in a behavioural priming paradigm is another area for future work. The short sentences and monosyllabic target words used in the current research did not allow for the examination of the timecourse of rhythmic priming, i.e., does entrainment strengthen over time?

7.2.4.2 Addition of visual cues

In all of the priming studies presented in this thesis the stimuli have been purely auditory. In everyday speech listening situations, it is likely that visual information will also be available. A speaker's natural head movements have been shown to enhance speech perception in noise (Munhall et al., 2004). The head movements were related to the prosody of the speech, and so it may be that the visual information provided additional cues to strengthen temporal expectations. The inclusion of visual cues also influences neural entrainment to speech (Power et al., 2012).

It has also been shown that hearing-impaired listeners gain a similar amount of benefit from endogenous visual cues for when to listen compared with normal-hearing listeners (Best et al., 2007a). Combining these two ideas, perhaps comparing an auditory-only with an audio-visual priming paradigm could elucidate how hearing-impaired listeners form temporal predictions. Are they able to orient temporal attention based purely on auditory rhythms? If they do not perform as well as normally-hearing listeners, then perhaps the combination of auditory and visual prosodic cues could compensate for the difference. If so, perhaps participants could be trained to use visual cues to orient temporal attention to assist with speech perception in noise.

7.2.4.3 Encourage endogenous attention

The focus in the current research was on automatic orienting of temporal attention via rhythmic priming, and so endogenous orienting of attention was discouraged. However, it may still have played a part in some cases, as discussed in Chapter 4.

With the simple isochronous sequence used in Experiment 2, or the simple speech prime in Experiment 5, it would be straightforward to deliberately orient attention to the predicted target location. Future research could investigate whether it is possible to endogenously orient temporal attention during speech listening in order to enhance rhythmic priming effects. If this were possible, then this could potentially be utilised in a training paradigm as well.

7.2.4.4 Rhythmic stimulation

The inadvertant discovery in Experiment 6 that performing a beat perception task prior to a sentence-in-noise test might improve perception may be worth pursuing in its own right. It has previously been shown that children with language disorders perform better on a syntactic judgement task when they listened to music with a regular beat prior to starting the task (Przybylski et al., 2013).

Perhaps focusing on the beat of musical excerpts prior to undertaking the matrix sentence test had a similar preparatory effect. Further studies would be required to see if this was indeed the case, and if the effect would extend to other speech stimuli with less regular rhythms.

7.3 Question 3: Can short-term beat training improve speech perception in noise?

The new-found knowledge that beat perception could enhance speech perception in noise via temporal prediction mechanisms was used to inform the design of a training programme. An established method of music teaching (Dalcroze Eurythmics) was adapted to focus on developing beat perception skills through synchronising movements to music. The impact of this training was evaluated for a group of older adults. Small improvements in speech perception thresholds in noise were observed after four weeks of training, although caution should be exercised when interpreting these results.

This study had considerable limitations – a small sample size and no active control group, for example – and future directions for building on this research are discussed below. For a preliminary pilot study, the results were quite promising and suggest that audio-motor musical beat training may be worth pursuing as a potential tool for improving speech perception in noise. However, the results are not conclusive and further training studies will be needed to verify if this is the case.

7.3.1 Considerations for future training studies

The training study presented in Chapter 6 had considerable limitations, including a small sample size, lack of an active control group, and no way to objectively measure participants' progress in the trained activities. Although the goal of the research was to investigate short-term training, four weeks may have been too short, especially given that the homework activities were not as successful as originally conceived. All of these things should be considered in future studies, along with some other ideas discussed here.

7.3.1.1 Target groups

For Experiment 6, it was decided to train older adults as speech perception in noise has been shown to decline with age (see Section 1.6.2).

An additional advantage in training this group is that the hypothesised mechanism by which beat perception might transfer to speech – i.e., rhythmic priming – is an automatic process which is not dependent on working memory. Since speech perception in older adults is adversely affected by cognitive decline, training to enhance a mechanism that is independent of cognitive demands could offer clear benefits if successful.

However, the older adults recruited for the training study did not display the expected deficits. Although their speech reception thresholds were significantly worse than for the young adults in Experiment 1, they reported no particular difficulties with listening to speech in noisy environments.

Future training studies should consider targeting groups who definitiely have room to improve (see Section 7.1.4). If a connection can be found between poor beat perception and poor speech perception in noise for a specific population, then that population would be an ideal target group for a future training study. As the intention is to train musical beat perception and evaluate any transfer to speech perception, it makes sense to select participants who have the potential to benefit. This would also provide a truer representation of whether musical training can be used to help those who struggle with speech perception in noise, which was the original motivation for this research.

7.3.1.2 Development of intermediate outcome measures

As well as coming up with ways to directly measure improvements in trained tasks, it may be possible to use intermediary measures. If the trained task is synchronisation with a beat, and the final outcome measure is speech perception in noise, then an intermediate measure could be part way through the hypothesised transfer mechanism. This was the intention behind using the beat perception test, but unfortunately it was not sufficiently sensitive to training differences as several participants scored highly at baseline. Another option could be to use a priming paradigm with complex rhythms to see if the priming effect increases as beat perception improves.

7.3.1.3 Individual differences

As discussed in Chapter 6, there were some participants who were less likely to benefit from the training as they already had good beat perception, possibly due to musical or dance experience. This highlights the importance of an individual differences approach to training interventions.

It was suggested above that targeting a clinical population who actually do struggle with speech perception in noise is likely to produce more training improvements. However, it may not be that simple. Speech perception in noise is a complex task, and it is likely that beat perception and rhythmic priming account for just a small part of the puzzle. There may be some individuals who have deficits in both skills and who may therefore benefit from musical beat training. For others, speech perception in noise might be challenging for some other reason unrelated to beat perception.

It is also important to take participants' personal preferences into account. An argument in favour of musical training is that it is enjoyable and likely to encourage compliance. However, for some individuals music may not interest them and so this would not be the case.

7.3.1.4 Creating a music–speech hybrid

The goal of the current research was not to identify the best possible training programme for speech perception in noise, but rather to test whether musical beat training would be one possibility.

There are elements of the training which were successful. Participants enjoyed the sessions – both the activities and the social aspect – and the retention rate was 100%, showing that the training definitely satisfied the emotion criterion of the OPERA hypothesis (Patel, 2014). The training was also multimodal, which has been shown to enhance benefits and plasticity compared to purely auditory training (Lappe et al., 2008, 2011).

Future training studies should retain these elements while considering if a purely musical approach is the best option for improving speech perception in noise. The potential benefits of music in terms of enjoyment and compliance have already been discussed (see Section 1.1.4), and beat perception does appear to be a suitable skill to target. However, this is likely to be only a small part of the picture.

It may be that the ideal training programme would involve a mixture of musical and speech-based activities. For example, adding lyrics to the music could be useful as song lyrics are often aligned such that stressed syllables occur on the beat of the music. Poetry, especially that with fixed rhythmic structures such as limericks, or even rap could also be used to develop participants ability to entrain to regularities in speech, while still retaining the enjoyable variety that is associated with musical training.

7.4 Conclusion

The goal of this thesis was to investigate the potential of musical training as an intervention for improving speech perception in background noise.

The key findings from the current research are that:

1. musical beat perception is associated with speech perception in noise
2. rhythmic priming enhances the perception of targets in noise

In conclusion, musical training does have some potential for use as an intervention for speech perception in noise. Any future attempts at designing such a programme should consider musical beat perception as a useful skill to target.

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