THE DYNAMICS OF AUDITORY STREAM SEGREGATION FOR TONE SEQUENCES WITH GRADUALLY AND ABRUPTLY VARYING STIMULUS PROPERTIES

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The dynamics of auditory stream segregation for tone sequences with gradually and abruptly varying stimulus properties

The nine experiments presented within this thesis explored the dynamics of stream segregation in repeating ABA tone sequences with gradual or abrupt changes in their acoustic properties. Experiments 1-6 used a continuous monitoring method to investigate the effect of these changes on the number of streams perceived (1 or 2). Experiments 1 and 2 demonstrated that abrupt and gradual changes in sequence base frequency had a much stronger effect on the build-up of streaming over time than those in interaural time difference (ITD), an outcome consistent with either functional or neural accounts of the build-up of segregation. Experiments 3 and 4 demonstrated that abrupt changes either in timbre (using pure tones and narrowly spaced tone dyads) or level could produce resetting (partial loss of build-up) but that the direction of the transition was important. Notably, an overshoot in stream segregation followed the tone-to-dyad transition, despite no significant change in the pattern of peripheral excitation. Experiments 6 and 7 demonstrated that resetting was not a result of correlated changes in A and B tone subsets. In both experiments, anti-correlated level changes tended to produce resetting (B↑A↓) and overshoot (B↓A↑), respectively. This outcome favours a neural mechanism of build-up based on subtractive adaptation. Experiments 7-9 investigated the influence of an induction sequence on the perception of a subsequent test sequence. Experiments 7 and 8 achieved capture of a tone subset in the test sequence by adjusting the difference in frequency or level between inducer tone subsets, such that only one subset matched its test-sequence counterpart. This resulted in greater stream segregation. Experiment 9 attempted capture using a harmonic complex synchronous with the lower subset. However, the fusion of the synchronous complex with the corresponding tone subset failed to disrupt capture, presumably because it did not change the rhythm of the sequence. Overall, these experiments demonstrate that abrupt changes in stimulus properties can cause resetting of build-up or overshoot, depending on the nature of the transitions, and stream capture can be achieved by manipulating the difference between tone subsets in an inducer.

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Key Phrases: Auditory Perception, Auditory Scene Analysis, Stream Segregation, Build-up, Stream Capture.

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Abbreviations

ERB	Equivalent Rectangular Bandwidth
FB	Fission Boundary
ILD	Interaural Level Difference
ITD	Interaural Time Difference
TCB	Temporal Coherence Boundary
TRT	Tone Repetition Time
Δf_{AB}	Frequency separation between 'A' and 'B' tones
Δf_i	Frequency separation between 'A' and 'B' tones in the inducer sequence
Δf_t	Frequency separation between 'A' and 'B' tones in the test sequence

Dedicated to Bhagawan Sri Sathya Sai Baba,
who had faith in me when I had none left.

Chapter 1

Introduction

1.1 The problem of auditory scene analysis

Everyday hearing and communication occurs within complex and changing environments. On a given day, we may move between a number environments—from a morning walk in the park, to a quiet day working in an open-plan office, then dinner in a busy restaurant. In all of these situations, we are able to communicate with those around us and choose which sounds we wish to attend to. Despite the complexity of these listening situations, many studies in the field of auditory perception have employed simple, unchanging stimuli in laboratory-based experimental setups. Whilst such investigations have furthered our understanding of the human auditory system, the acoustic stimuli used differs greatly from the sounds encountered in our everyday listening environments.

It is therefore important to consider how the auditory system makes sense of a varied and continuously changing 'auditory scene'. The purpose of auditory perception is to build a mental representation of the world around us and this process of analysing the acoustic input to form a representation of separate and distinct sound sources in the surrounding environment has been termed auditory scene analysis (Bregman, 1990).

The question of how the auditory system performs this analysis can broadly be divided into two areas. Firstly, it must organise sounds sequentially over time. Sounds originating from the same source should be grouped together whilst those emerging from different sources are separated into streams. A stream can be considered to be the mental representation of a single auditory source. Secondly, the auditory system is also required to organise simultaneous sounds—in particular, at any one moment in time it must separate independent but temporally overlapping sounds.

The experiments presented within this thesis investigate the sequential organisation carried out by the auditory system using the experimental paradigm of stream segregation. Particular focus has been placed on the dynamics of stream segregation and the effect of changing stimulus properties. This use of stimuli with changing properties is an attempt to move from the traditional setup of simple stimuli with unchanging properties, towards those encountered in 'real world' listening environments. The focus is on understanding the effects of changes in sequential properties, and to facilitate this the acoustic properties of the individual sounds comprising a sequence are kept simple.

1.2 Stream segregation

Auditory stream segregation has typically been explored using alternating sequences of pure tones of high and low frequency. A common configuration of the alternating-tone sequence is as a series of 'ABA-' triplets, first developed by van Noorden (1975). These sequences consist of alternating low (L) and high (H) frequency pure tones followed by silence—either 'LHL-' or 'HLH-' sequences. These sequences can be perceived in two, alternative ways as shown in Figure 1.1. The first is as a single, *integrated* stream where listeners perceive a characteristic 'galloping' rhythm. The second is, however, when the sequence is *segregated*, i.e., it is heard as two monotonous streams—in the case of 'LHL-' sequences, one repeating sequence of high frequency tones and a faster sequence of low frequency tones.

1.3 Measures of stream segregation

1.3.1 Subjective and objective psychophysical measures

A number of studies, particularly the earlier work on stream segregation, have used subjective methods to obtain a measure of stream segregation. Typically, participants

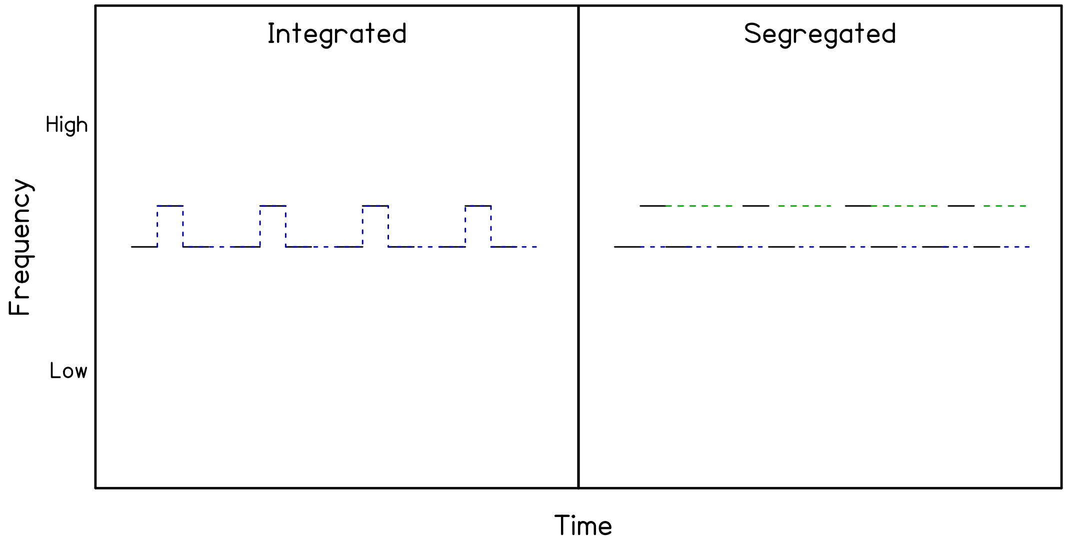

Figure 1.1: Tones arranged in an ABA- configuration as initially developed by Van Noorden (1975). In an integrated percept the low (A) tones and high (B) tones are grouped together. In the segregated percept, the high (B) tones form two distinct monotonous streams—a slower high pitched stream of B tones and faster sequence of lower pitched A tones. Dots indicate perceptual links between tones.

are instructed to report the degree of segregation perceived. In some cases a subjective rating is made at the end of a test sequence using a scale or forced choice alternative (e.g. Rogers and Bregman, 1993, 1998; Snyder et al, 2009; Haywood and Roberts, 2010). Other measures provide additional information on the alternations between integrated and segregated percepts by instructing listeners to continually monitor their perception of a stimulus and report whether the sequence is integrated or segregated throughout (e.g. Roberts et al., 2002, Denham and Winkler, 2006, Pressnitzer and Hupé, 2006, Kondo and Kashino, 2009, Bendixen et al., 2010). Lastly, listeners are instructed to adjust a physical stimulus parameter (e.g., frequency separation or rate) to estimate the segregation threshold (Miller and Heise, 1950; Anstis and Saida, 1985; Bregman, 1978b). This method provides a measure of the threshold in physical units—e.g., threshold = 6-ST frequency separation.

Regardless of the differences of each of the above approaches, they rely on introspection. Although common patterns can be observed across listeners, a common criticism of these methods is they cannot be independently verified and could potentially reflect response bias. Nonetheless, these subjective assessments can be regarded as providing a direct measure of the degree of streaming perceived by listeners, rather than one that must be inferred via changes in task performance. Bregman (2015) notes that despite criticism of direct reporting as being 'too subjective', there is a strong case for asking listeners what they *actually hear* in order to further understanding of auditory perception.

Objective (i.e., performance-based) measures overcome the above criticisms to some extent. Typically, participants are required to complete a task for which performance should be affected by streaming. These tasks rely on differences in pattern recognition based on within- vs. across-stream comparisons. In general it is easier to make judgements on information within in a single stream rather than cross-stream.

Some tasks show improved performance when an integrated percept is maintained by exploiting the advantages provided by an integrated percept—particularly the rhythm or timing of the sequence. Temporal discrimination tasks have commonly been used in this context, such as the 'temporal slip' or 'delay detection' tasks utilised by Roberts et al. (2008) and Thompson et al. (2011). Listeners are better able to detect a delay in presentation of the 'B'-tone within a 'ABA-' sequence when an integrated percept is maintained, as it is perceived as a 'skip' in the gallop percept.

Frequency discrimination tasks, such as the interleaved melody task, are often used to exploit the advantages of a segregated percept. Dowling (1973) presented two melodies interleaved in time so that successive tones come from different melodies. When their pitch ranges did not overlap, the tones were grouped into two distinct streams so that either melody could be attended and perceived. Cusack and Roberts (2000) used an interleaved melody task that required listeners to detect a melodic alteration. The tones of a short, arbitrary sequence (the 'target melody') were presented with 'distractor' tones, and the timbre and frequency range of the distractors was varied across conditions. In each trial the target melody was played followed by two intervals containing a melody interleaved with the same distractors. In one, the true target was presented, but the other interval contained a false target. Listeners were required to identify the interval with the true target. The size of the perturbations in frequency on each target note was adjusted adaptively to find threshold.

The use of subjective and objective measures in conjunction tend to provide comparable results. Billig and Carlyon (2016) developed a combined subjective and objective streaming task. Listeners were required to continuously attend to 18.5-s long 'ABA-' sequences and detect rhythmically deviant triplets—giving both tasks equal priority. The latter task would be facilitated by a more integrated percept, and scores would be expected to be worse for triplets occurring later on in the sequence if build-up was occurring. Consistent with this, listeners' tended to report more segregation later on in the sequence and at greater frequency separations, with limited dual-task interference.

1.4 Factors affecting stream segregation

Whether a sequence of tones is perceived as integrated or segregated can be influenced by certain stimulus properties. The effect of frequency separation is perhaps one of the best documented. An early study on the effect of frequency separation on streaming was carried out by Miller and Heise (1950) using a continuous sequence of pure tones ('ABAB...') which alternated at a fixed rate of 5 Hz (i.e., 10 tones/s). One tone remained at a fixed frequency, ranging from 100 Hz to 10 kHz. The frequency of the other tone was varied by the participant until the sequence was perceived as two streams; the threshold at which the percept changed from integrated to segregated was termed the trill threshold. For base frequencies of up to 1 kHz, the ratio of $\Delta f/f$ (where Δf is the frequency difference between the two tones at the trill threshold, and f is the frequency of the fixed tone) remained constant at 0.15. As base frequency was increased beyond 1 kHz, the ratio began to fall, indicating a greater tendency towards a segregated percept.

The strong influence of Δf, in addition to the rate of presentation, on the perception of tone sequences was also established by van Noorden (1975). He carried out much of the initial work into the phenomenon of streaming, using 'ABA-' sequences. van Noorden (1975) compared the percepts of temporal coherence (integration) and fission (segregation) noting the influence of participant listening 'set' on the percept. Participants were instructed to listen in one of two ways, either selectively—where the listener attempted to maintain a segregated percept—or comprehensively—where the aim was to retain an integrated percept. This produced two different measures of the threshold between integrated and segregated percepts. The threshold obtained with the participant listening comprehensively, was termed the temporal coherence boundary (TCB). The fission boundary (FB) was the threshold derived when listening selectively.

FIGURE 1.2: The temporal coherence (TCB) and fission boundaries (FB) derived from the average of 3 listeners.Reproduced from Van Noorden (1975).

van Noorden (1975) noted that Δf influenced the tendency to perceive the stimulus as integrated or segregated. At Δfs exceeding the TCB, a segregated percept was always perceived. Below the FB, the percept remained consistently integrated. At Δfs lying between these 2 thresholds, the percept could be either. He also established that tone repetition time (TRT) influenced the degree of segregation. At longer TRTs (i.e., at slower sequence rates), Δf could be greater before the ability to perceive an integrated percept was lost and TCB increased with TRT. However, FB remained fairly independent of TRT (as shown in Figure 1.2).

1.4.1 Gestalt theories of stream segregation

This initial work on streaming carried out by Miller and Heise (1950) and van Noorden (1975) was set in the context of the Gestalt principles of perceptual organisation by Bregman (1990). The Gestalt psychologists proposed that sensory systems performed grouping and analysis on the basis of laws such as proximity, similarity, continuity and common fate (Köhler, 1929; Koffka, 1935). It would follow that tones which had similar physical properties (e.g. the same level or the same duration) or common fate (e.g. such as having the some onsets and offsets) are more likely to originate from the same sound source. The previously described effect of Δf can be considered consistent with the principle of proximity, i.e. tones that are closer in frequency are more likely to perceived as originating from the same sound source as those with larger frequency separations. These principles can be considered 'primitive', reflecting an automatic process, and were initially explained using peripheral accounts of streaming.

1.4.2 The peripheral channelling hypothesis

The strong influence of Δf on streaming could be accounted for by differences in the excitation pattern on the basilar membrane evoked by pure tones of different frequency. Tones with smaller Δfs are more likely to stimulate overlapping regions of the basilar membrane, resulting in the percept of a single stream. In the case of larger Δfs, the two tones are more likely to stimulate maximally distinct areas of the basilar membrane, leading to a segregated percept. In fact, many earlier studies proposed that a 'peripheral channelling' hypothesis could account for the influence of a number of stimulus properties on streaming. Beauvois and Meddis (1996) proposed a model of peripheral channelling based on the bandpass filtering carried out by the basilar membrane. They suggested that greater overlap in the excitation pattern elicited by two tones increased the likelihood of an alternating-tone sequence being perceived as integrated.

Hartmann and Johnson (1991) used an interleaved melody task to examine the effect of 12 different factors on the ability of listeners to hear out known melodies from a mixture. When the factor varied in spectral composition, ear of presentation or frequency separation, the two melodies were heard out with greater ease—leading Hartmann and Johnson (1991) to propose that streaming was primarily mediated by peripheral channelling.

Experiments carried out by Rose and Moore (2000, 2005) using pure-tone sequences were consistent with this model. They measured the fission boundary of alternating 'ABA-' tone sequences with different Δfs and overall presentation levels. When expressed as the difference in equivalent rectangular bandwidth (ERB) number—denoted by ΔE—between A and B tones, FB remained fairly constant across frequency. The ΔE at the FB rose with increasing presentation level. This would be expected in light of the broadening of the auditory filters at higher levels, in accordance with the accounts of peripheral channelling proposed earlier.

It is notable that most changes that can be made to a complex tone inevitably produce peripheral channelling cues. Exceptions to this include changes in F0 for unresolved harmonics passed through a fixed bandpass filter and changes in temporal envelope for sounds whose spectrum remains constant.

1.4.3 Factors affecting streaming independently of peripheral channelling

A number of subsequent studies have revealed the influence of factors that cannot be adequately explained by peripheral channelling, and suggest involvement of other areas of the auditory system. Differences in temporal envelope have been shown to affect streaming. This was first noted by Dannenbring and Bregman (1976) who found that sequences composed of alternating tones and narrowband noise (with similar excitation patterns) were heard as considerably more segregated than tone-only or noise-only sequences. Further work by Iverson (1993), using tones produced by orchestral instruments, demonstrated that the degree of perceived segregation of the sequences was influenced not only by differences in spectral frequency but also by the temporal envelope of the tones.

Singh and Bregman (1997) created timbre differences in complex-tone sequences by varying both the spectral composition and amplitude envelope of the tones. The fundamental frequency (F0, i.e., pitch) difference between 'A' and 'B' tone subsets was increased until the FB was reached. Although conditions where both cues combined promoted segregation the most (i.e.) required the lowest F0 difference for listeners to perceive the sequence as segregated, spectral cues only also promoted segregation. This was the case for temporal envelope cue only cases, however to a lesser extent.

Using 'ABA-' sequences of amplitude-modulated broadband noise, where the difference in modulation rate between noise bands was varied, Grimault et al. (2002) found that greater differences in modulation rate led to a more segregated percept. Cusack and Roberts (2000) used an interleaved melody task, where performance was improved by perception of the tones as segregated, to demonstrate that narrowband noises (with only slightly different excitation patterns to pure tones) were still able to increase segregation level.

Roberts et al. (2002) determined that phase differences could also influence streaming. Using unresolved harmonics filtered through a passband, listeners were required to perform a delay detection (irregular rhythm) task where increases in segregation level reduced the listener's ability to detect an increasingly irregular rhythm in either the 'A' or 'B' tone subsets. For such stimuli, changing the component phase (Roberts et al., 2002) provided a perceptual change in the quality of the stimuli without introducing peripheral channelling cues. The phase changes used (cos/alt/rand) affected both pitch and timbre. Phase differences were shown to increase the threshold for discrimination of the irregular rhythm. This was supported by results of a second subjective experiment, where difference in phase between subsets led to an increase in the proportion of time the sequence was perceived as segregated.

In addition to ear-of-presentation, lateralisation cues created by interaural time differences (ITD) and interaural level differences (ILD) have been investigated in the context of streaming. The influence of ITD cues, unlike ear of presentation or ILD, is independent of peripheral channelling. Hartmann and Johnson (1991) noted that introducing ITD differences between two interleaved melodies aided segregation of the melodies. The effect, however, was not as strong as that elicited by differences in ear-of-presentation. When comparing ITD and ILD effects on listeners' ability to hear out target rhythms with masker tones interleaved, Sach and Bailey (2004) found that the masker was most effective when the spatial position (cued by both ITD and ILD) was the same as the target rhythm. When the ILD of both masker and target was kept the same, different ITDs aided hearing out the target sequences. Conversely, Boehnke and Phillips (2005) found weak effects of ITD in both objective (gap detection and temporal asymmetry detection) and subjective tasks (continuous assessment) in comparison with the moderately strong effects of ILD and ear-of-presentation.

Stainsby et al. (2011) also used an objective measure, this time a rhythm irregularity task for a sequence of 'A' and 'B' tones. Thresholds for detection of the irregularity were much lower when the tones had an ITD difference exceeding 1 ms (consistent with a typical maximum ITD of approximately 1 ms for opposite lateralisation using an adult male head). Below that, any reduction in threshold was much less substantial.

As larger ITDs could have further affected the rhythm of the sequence, enhancing listeners' abilities to perceive the irregularity, the authors concluded that any effect of ITD on streaming was likely to be weak.

In a recent review Moore and Gockel (2012) note that, particularly in the case of ITDs, the perceptual salience of the difference determined the degree to which it would impact on segregation level. The influence of a factor could be affected by the task utilised to measure the extent of segregation. Essentially any salient perceptual difference between subsets of sounds can assist their segregation and can also limit integration even when a task demands it. Most of the stimulus changes described here do introduce peripheral channelling cues, but even those that don't can demonstrate these same effects.

1.5 Dynamics of stream segregation: Build-up, resetting and decay

1.5.1 Build-up of stream segregation

Many studies investigating auditory streaming have used sequences whose properties remain constant. Accordingly, we still know relatively little about the dynamics of stream segregation.

The initial studies by van Noorden (1975) revealed that, for a given fixed TRT and Δf, the tendency to hear a segregated percept increased with time—a phenomenon termed build-up. Bregman (1978b) investigated build-up more systematically, using a continuous repeating sequence of high and low tones packaged into sequences of 4, 8, or 16 tones. These packages were alternated with 4 s silences to create an indefinitely repeating sequence. Listeners were asked to adjust the rate of presentation until the sequence was just perceived as segregated, thereby obtaining the FB. The FB was observed to decrease with increasing package length—i.e., the more tones per package, the slower the sequence rate at threshold.

Anstis and Saida (1985) generated alternating sequences of high and low tones ('ABAB...') by frequency modulating a pure tone with a square wave. Participants controlled the Δf adjusting it to maintain an integrated percept over time. Initially, the modulation rate had to be reduced rapidly to maintain an integrated percept. This tendency continued but slowed beyond approximately 10 s. Build-up tended to be more rapid for higher Δf or faster TRTs—factors that tended to increase the overall segregation level when elevated. From these studies, it is clear that build-up of stream segregation has two stages. The initial stage is characterised by a rapid increase in segregation level (up to the first 10 s), followed by a slower increase that may continue for up to at least a minute (Bregman, 1978b). Bregman (1978b) proposed that this process indicates an increasing biasing of the auditory system to perceive independent sound sources. He noted that the duration of this process - over seconds rather than milliseconds - indicated a 'conservative evidence accumulation process'. He argued that a more conservative mechanism served to stablise percepts, thereby preventing the auditory system from fluctuating rapidly between alternative percepts.

1.5.2 Decay

Bregman (1978) first reported that the build-up of the tendency to hear a segregated percept decays following the end of stimulus presentation. Beauvois and Meddis (1997) used a repeating low-frequency tone inducer (sequence = 10 s) followed by a silence ranging between 0 and 8 s and then by a 1.44-s test sequence of alternating low and high tones. The tendency towards segregation of the test sequence decayed with increasing duration of the silent interval. This effect was also seen by Cusack et al. (2004) in an investigation utilising 10 s 'ABA-' sequences followed by silent gaps of between 1 and 10 s before the next sequence.The effect of the preceding sequence on the percept of segregation for the next sequence was studied. Smaller gaps increased the probability of the next sequence eliciting a segregated percept, suggesting that there was a persisting effect of the previous sequence that decayed over time. This was also found by Snyder et al. (2008) who demonstrated that the effect of a preceding sequence could persist for at least up to 5.76 s, although it was noted to decay during this period.

1.5.3 Resetting

It has been established that build-up of stream segregation can be reset, at least in part, upon the introduction of an abrupt change into an otherwise stable sequence. Anstis and Saida (1985) discovered that build up was maintained throughout the course of a binaural presented test sequence. In the case where an inducer was presented monaurally prior to the test sequence in the contralateral ear, any build-up of stream segregation was lost. From this, they inferred that build-up was a peripherally mediated process of adaptation.

1.6 Factors affecting build-up and resetting

Factors affecting build-up and resetting were investigated more extensively by Rogers and Bregman (1993, 1998), using 'ABA-' test sequences preceded by an induction sequence (as shown in Figure 1.3). Rogers and Bregman (1998) evaluated the influence of introducing various discontinuities into the sequence properties. Perceived location was varied using ITDs, ILDs, and location of loudspeakers. The overall presentation level of sequences was also changed. The change in properties between the induction and test sequences were either sudden, gradual, or absent (no change). Sudden changes in properties had the greatest resetting effect, gradual changes had less and no change had no effect on build-up. Changes in ITD, ILD, and speaker location all had an influence on build-up, with speaker location (which provided both ITD and ILD cues) having the greatest resetting effect.

Rogers and Bregman (1998) suggest that the influence of location—an apparently irrelevant property to the process of segregation based on frequency difference—can be understood if the process of stream segregation utilises information collected in a 'multidimensional space' (including frequency, level, and location). Considering the question within this paradigm they posit two alternative theories of resetting induced by sudden and gradual changes. First, that a gradual change in location brings the stimulus closer in properties to the test sequence. This allows the evidence-accumulation process for the tones centred at the frequencies of the test sequence to begin prior to start of the test sequence. The tendency for segregation, therefore, begins to build up earlier than for the sudden change condition. The alternative theory is that a sudden change defines an acoustic boundary, actively restarting the evidence-accumulation process.

An earlier study by Rogers and Bregman (1993) used different types of induction sequence, to establish whether similarity between test and induction sequences in their

FIGURE 1.3: Induction-test sequence setup used in Experiment 1 of Bregman (1993). Dark rectangles represent pure tones, the large striped rectangle represents white noise. The solid, vertical line denotes the unsigned boundary between induction and test sequences, whilst the broken, vertical lines show cycle boundaries. Reproduced from Rogers and Bregman (1993).

acoustic properties, rhythmic predictability, and tone duration would affect the extent of segregation. Inducers were composed solely of a sequence of short high tones, a single continuous high tone or white noise burst followed by monotic or diotic 'ABA-' test sequences. The high tone inducers were presented at either regular or irregular intervals.

Rogers and Bregman (1993) found no effect of temporal regularity on streaming judgments, an outcome which contradicted the suggestion that segregation is mediated by sequential predictability (Jones, 1976). Accompanying monotic 'ABA-' induction sequences with a contralateral presentation of tones that disrupted the gallop rhythm prevented build-up. Binaural induction sequences failed to elicit as high a rate of build-up as monotic sequences that were identical to the test sequence. Both these results indicate that build-up is not mediated by ear-specific neural populations.

1.6.1 Resetting or Failure to Transfer?

Rogers and Bregman (1998) proposed two alternative accounts for the fall in segregation following an abrupt change at the inducer-test boundary. The first was that build-up had failed to transfer over the inducer-test boundary. The second was that the change had actively reset the process of build-up.

Roberts et al. (2008) used an objective task to address the question of whether build-up was reset or failed to transfer from the inducer to the test sequence. The inducer-test sequence format used aided comparison between this study and the subjective-measure investigation carried out by Rogers and Bregman (1998). The standard inducer comprised solely of low frequency tones with a test sequence of 3 cycles of alternating low and high tones. The inducer tone frequency was either the same as for the low frequency tones in the test sequence (1 kHz) or 2 octaves below (250 Hz). The inducer was a continuous 1.95-s tone and silence of 50 ms, a regular inducer of 10 equally spaced 50-ms tones, or an 'extended' inducer of 10 x 150-ms tones. The Δf of the test sequence was varied between 0 and 12 semitones.

Each trial consisted of 2 intervals, one of which was the standard isochronous (regular) sequence and the other was an anisochronous (irregular) target sequence with delayed high frequency tones. Participants were required to detect whether the sequence was irregular or regular. As perception of temporal relationships within a sequence of sounds is known to be impaired if the sounds are heard in different auditory streams, participants were more likely to detect the delay in a sequence if an integrated percept was maintained. It could therefore be expected that delay detection would be worse if segregation had built-up, but better if the inducer had a resetting effect.

The outcomes of this Roberts et al. (2008) objective study were largely consistent with the findings of Rogers and Bregman (1998). The regular test sequences induced increasing temporal discrimination thresholds as a result of build-up. As expected, abrupt changes in level and lateralisation at the inducer-test boundary resulted in maximal resetting as indicated by improved delay detection. Some discrepancies were noted in certain conditions (e.g. loud-to-soft transitions and random inducer rhythms resulted in greater resetting according to an objective measure of streaming). Roberts et al. (2008) suggest that this may be due to 'listener set', with task differences affecting the degree to which acoustic cues are used, i.e. those cues that aided the temporal discrimination task were more likely to be used.

Haywood and Roberts (2010) looked at the effect of introducing a single deviant stimulus into the induction sequence. A standard inducer of 10 low frequency tones was followed by a test sequence of 3 cycles of alternating low and high tones. The final 'deviant' induction tone was varied in frequency, level, and duration, or it was replaced with silence. Including a single deviant at the end of the induction sequence typically caused resetting of build-up. As the majority of the sequence had remained unchanged, this fall in the extent of segregation could be considered to indicate an an active resetting process rather than a failure of build-up to transfer.

1.6.2 Predictability and temporal regularity

More recently, a number of studies investigating the dynamics of streaming have focused on the influence of predictability and temporal regularity. The majority of predictability studies have used objective measures to determine the influence of stimulus uncertainty/irregularity on streaming. Bendixen et al. (2010) and Andreou et al. (2011) demonstrated that introducing increasing amounts of jitter into sequences, decreased the tendency to hear the sequences as segregated. This would indicate that increasing the amount of temporal variability between the elements of the sequence either increases the tendency to hear a sequence as integrated or disrupts build-up. Using continuous assessment of 4-minute-long sequences, Bendixen et al. (2013) evaluated the influence of feature similarity and predictability, noting that only similarity affects the initial stage of percept formation. However, both similarity and predictability interact to influence the stability of the second stage of streaming (i.e., competition between alternative organisations).

1.7 Promotion of segregation

The biasing of the perception of a sequence has been investigated in two ways. The first has been the influence of a previous sequence on the subsequent sequence and the second is with the use of a constant-frequency inducer.

The effect of a prior sequence on current percept has been explored by varying the frequency separation of an alternating tone sequence (Snyder et al., 2008, 2009a, 2009b, 2011). Snyder et al. (2008, 2009a, 2009b, 2011) presented sequences of 'ABA-' triplets separated by a silent interval (> 1.4*s*). Listeners were prompted to report whether they perceived the sequence as integrated or segregated. A smaller frequency separation in the previous trial consistently led to a more segregated percept of the current trial, whilst a larger separation in the previous trial produced a more integrated percept of the current trial.

The second approach, also referred to as 'stream capture' (cf. Bregman and Rudincky), used a constant-frequency inducer (Bregman and Rudnicky, 1975; Beauvois and Meddis, 1997; Rogers and Bregman, 1998; Roberts, Glasberg, and Moore, 2008; Haywood and Roberts 2010, 2011, 2013). When matched to one of the tone subsets of an alternating-frequency test sequence, the introductory constant frequency sequence induced a highly segregated percept in the following test sequence. This effect was near-instantaneous, and is therefore distinct from the processes mediating build-up, and accordingly termed 'stream capture'. Haywood and Roberts (2013) explored this difference between build-up and stream capture using either a constant frequency (CF) or alternating frequency (AF) inducer that contained single deviant (the final inducer tone was replaced by silence). Here the CF inducer promoted substantially more segregation at test-sequence onset than did the AF. Unlike the CF case, there was no resetting in the AF deviant condition perhaps because a single tone was not salient enough to disrupt the integrated percept of this sequence.

1.8 Bistability

Although the tendency towards a segregated percept is observed to build-up with time, the percept of a repeating sequence rarely remains either integrated or segregated indefinitely. This alternation in perception between one and two streams when listening to an 'ABA-' sequence is comparable with the bistability of visual stimuli. Bistability is a term used to describe the spontaneous perceptual alterations evoked by an unchanging visual stimulus presented over time (Pressnitzer et al., 2011). Pressnitzer and Húpe, (2006) considered build-up of auditory stream segregation in a bistability paradigm, comparing it to the perception of plaid stimuli in vision.

When seen moving through a circular aperture, a network of crossing lines is either perceived as a single plaid moving in a one direction or as two gratings sliding in opposite directions on top of one another. The moving plaids were used as the percepts corresponded; either one stream/one plaid or two streams/two gratings were perceived. Participants either listened to an 'ABA-' sequence or observed moving plaids for 4 minute intervals. They found that the alternating integrated and segregated auditory percept met the characteristic criteria for visual bistability as defined by Leopold and Logothetis (1999). First, the integrated and segregated percepts were largely exclusive, with listeners rarely reporting an intermediate percept. Second, percept durations were random, following a log normal statistical distribution, and listeners were unable to influence greatly the duration of specific percepts.

It has been argued that auditory streaming is purely stochastic and that build-up is simply an artefact of averaging across trials and across participants in the initial stages of streaming; a combination of the auditory system's initial bias towards the integrated percept (Bregman, 1978) and the 'inertia' of the first percept (Denham and Winkler, 2006; Pressnitzer and Húpe, 2006; (Húpe and Pressnitzer, 2012). However, Anstis and Saida (1985) note that the depth reversals seen in the Necker cube are the result of a purely stochastic process. There are no long-term trends over time in favour of one percept, whereas there is a clear trend towards segregation observed in presentation of long, alternating sequences. It is worth noting that a drift in the long-term trend towards one percept is not incompatible with a stochastic process. Despite the bistable nature of the percept, changes over time in the overall likelihood of hearing either of the two percepts can be obtained by averaging data across trials and participants.

1.9 Attention

Carlyon et al. (2001) presented 20-s 'ABA-' sequences in the test ear, with a series of noise bursts in the contralateral ear. In that condition, the final level of segregation was less than when attending only to the test sequence, indicating an absence or loss of build-up. Thompson et al. (2011) used a similar test setup. However, rather than being asked to report the extent of segregation, participants were required to detect a delay on one of the 'A' tones in the sequence. The results of this task support the findings of Carlyon et al. (2001) in that delay detection thresholds were longer for targets late in the sequence when listeners attended throughout than when they switched their attention to the task only shortly before the late targets. Experiments by Cusack et al. (2004) revealed that build-up could occur even when the sequences were not attended to, in contrast to the findings of Carlyon et al. (2001) and Thompson et al. (2011). This would suggest that rather than the failure of build-up to occur in unattended to sequence, it is the switch in attention has a resetting effect on any build-up that has occurred.

If considered a purely automatic process, mediated by peripheral factors then top-down influences would not affect streaming. Contrary to this, Carlyon et al. (2001) demonstrated that streaming of monaurally presented alternating 'ABA-' sequences could be influenced by attention. The initial 10 s of the alternating tone sequence was presented concurrently with a series of noise bursts in the contra-lateral ear. The noise bursts could either be 'approaching' (increasing in intensity) or 'departing' (decreasing in intensity). Listeners were required to identify whether the noise bursts were approaching or departing and record this response, ignoring the alternating sequence until the end of the noise bursts. Once the noise bursts had stopped, listeners began recording their percept of the 'ABA' sequences. These showed a low initial level of segregation which increased over the next few seconds, interpreted as indicating that no build-up had occurred during the initial portion of the sequence. Alternatively streaming may have occurred in the initial unattended portion of the sequence which was reset on switching attention from the competing noise burst task to the 'ABA-' sequences (Cusack et al., 2004). This was consistent with the results obtained by Thompson et al. (2011), who used a similar stimulus in a temporal discrimination task. However electrophysiological studies have provided some evidence supporting the assertion that attention is not essential for build-up to occur.

1.9.1 Electrophysiological measures of streaming

The mismatch negativity (MMN) is a component of the human auditory evoked potential, with maximal deflection approximately 150 ms following a deviation in the established properties of an ongoing stimulus. Electrophysiological studies of streaming have utilised the MMN to examine the dynamics of auditory streaming, as the listener's attention is not required to derive this measure. It can be elicited when listeners are performing another task (such as reading or performing a visual task) and accordingly is considered a pre-attentive process (Näätänen and Winkler, 1999). The MMN is considered an indication of auditory sensory memory because it is elicited upon detection of a deviant in a previously unchanging series. A number of studies demonstrated that MMN can be elicited on presentation of a deviant stimulus, even when the sequence is not attended to (Sussman et al., 1999, 2003; Ritter et al., 2006).

Sussman et al.(1999) used this approach to explore streaming in sequences of alternating tones. Listeners were instructed to ignore the sequences and read a book during the experiment. They varied the presentation rate of the alternating tones, and presented a 3-tone deviant in some test sequences, which could be more easily detected when the high and low tones were perceived as two segregated sequences. The MMN was elicited in response to the deviant stimulus, more often in sequences with a higher tone repetition rate, consistent with the known effect of rate on segregation level.

1.10 Neural Accounts of Streaming

The first investigations into the neural basis of streaming were carried out by Fishman et al. (2001), who recorded multi-unit activity and local field potential from the primary auditory cortex of awake macaques. The A-tone frequency was set at that closest to the best frequency of the recording site, whilst the B-tone frequency was varied. At higher tone repetition rates and larger Δfs, the neural response to the B tones was attenuated, consistent with reports of a more segregated percept.

Fishman et al. (2001) suggested that this effect was mediated by a forward suppression, where the neural response to a tone is suppressed by the preceding one. This effect was more pronounced for tones that were further in frequency from the best frequency of the neural population recorded from. These findings were replicated by Micheyl et al., (2005) in single unit recordings of the primary auditory cortex of the awake macaque. They also noted that the responses to all tones decreased over the duration of the sequence, indicating multi-second adaptation or habituation of the neural populations.

These results were also observed in the cochlear nucleus of guinea pigs (Pressnitzer et al., 2008). In both studies, a habituation of neural responses is observed that follows a similar time-course to the build-up observed from psychophysical data. Pressnitzer et al. (2008) suggest that this 'slow-gain control' is mediated by long-term synaptic depression and fast recovery of peripheral neurons. It is important to note that these responses have only been obtained in responses to pure tones.

These results suggest that multi-second adaptation may provide a plausible neural basis of the build-up of streaming. These may occur as early as the cochlear nucleus and as late as the auditory cortex in humans. Obtaining neural responses to more complex stimuli is required to identify whether this process underlies streaming.

1.11 Questions remaining

The vast majority of studies into the dynamics of auditory stream segregation have utilised constant repeating sequences, with stimulus properties remaining fixed for the duration of the sequence. Also, experiments looking at factors affecting build up and resetting of stream segregation have mainly used an inducer-test sequence format (Rogers and Bregman, 1993, 1998; Roberts et al., 2008; Haywood and Roberts, 2010, 2013). The stimulus properties of the inducer are varied whilst the properties of the test sequence remain standard and the degree of segregation is often only measured once, at the end of the sequence.

Whilst resetting has been observed in response to abrupt frequency changes, there is little understanding of the reason for this drop in segregation level or the mechanism underlying resetting. The segregation promoting effect of a constant-frequency inducer noted by Rogers and Bregman (1993) and Haywood and Roberts (2013) is also little understood. Exploration of other factors that promote segregation or 'capturing' out subsets from the test sequence, may further understanding of the effect of context. Currently, the extent to which a common mechanism is involved for the stream-promoting effects of constant- vs. alternating-frequency inducers is unknown.

The isolated and unchanging stimuli typically used in experimental studies of the dynamics of stream segregation have very little in common with those encountered in everyday listening environments. The auditory system is required to perform stream segregation with stimuli that may vary greatly over time in pitch, timbre, loudness, and location. The investigations planned in this report aim to investigate the dynamics of stream segregation using stimuli somewhat closer to 'real-world' stimuli by utilising test sequences with changing stimulus properties. To avoid the complications of the effects of changes in excitation pattern, all the experiments reported here have used pure-tone sequences or variants that involve minimal changes in excitation pattern.

1.12 Overview of Experiments

This thesis explores stream segregation using two kinds of stimulus configurations. The first 3 experimental chapters focussed on the effect of changes in stimulus properties on the dynamics of streaming—i.e., build-up and segregation—in an on-going test sequence.

Experiments 1 and 2 aimed to establish whether changes in base frequency and ITD (both abrupt and gradual) had comparable effects on build-up and resetting of stream segregation. The direction and extent of these changes in sequence properties were varied to further establish whether the magnitude of a change affects the degree to which a percept was 'reset' and the duration of this resetting effect. Experiment 1 follows on from earlier work by Anstis and Saida (1985) who looked at the effect of only abrupt changes in frequency (using a nulling rate procedure) to examine the effect of abrupt and gradual changes in frequency on stream segregation. Experiment 2 uses the continuous monitoring method to replicate the results of Rogers and Bregman (1998) who investigated changes in ITD using an inducer-test format and one-off judgement to derive an overall measure of segregation for the test sequence.

Following on from this, Experiments 3 and 4 explored the effect of abrupt changes within otherwise constant sequences. Experiments 3 explored abrupt changes in timbre produced by pure tones and tone dyads. Experiment 4 used comparable changes in level. Together, these experiments demonstrated that a sudden change in acoustical properties can produce a resetting and an overshoot in stream segregation, without a significant change in the pattern of peripheral excitation for a given sequence of sounds, indicating that any perceptually salient change can influence segregation. Experiments 6 and 7 demonstrated that resetting did not occur as a result of the correlated changes in both tone subsets. In both experiments, anti-correlated changes were able to cause significant resetting, in addition to overshoot, which could be produced by subtractive adaptation of the neural populations responding to the tone sequence.

The last experimental chapter presented three experiments that used an inducer-test setup to explore the effect of an induction sequence on the perception of the subsequent test sequence. These experiments demonstrated that segregation promotion or capture of either tone subset can be achieved by adjusting the perceptual space (in frequency or level) between the inducer tone subsets, and these effects persisted throughout the course of a 12-20 s test sequence. Experiment 7 demonstrated that increasing the level difference between tone subsets, increased the segregation level of the subsequent test sequence. Both increasing and decreasing the frequency separations on tone subsets in the inducer for Experiment 8 also promoted effective capture of the test sequence tones, suggesting that the direction of the change did not affect capture. Experiment 9 used harmonically related tone complex synchronous with the lower tone subset to attempt capture. In contrast with the previous two experiments, the synchronous complex tended to fuse with the corresponding tone subset, maintaining the rhythm of the sequence and failing to disrupt capture.

Chapter 2

General Method

The experiments presented within this thesis employed behavioural measures based on introspection to obtain a measure of stream segregation. The two-alternative forced-choice (2AFC) experimental setup enabled subjective assessment of stream segregation for sequences of 'ABA-' triplets; the second tone (B) has a different frequency from the first and third tones (A), and the triplet is followed by a silence (-) of the same duration as the individual 'A' and 'B' tones. Although specific sequence properties were varied for each experiment, certain elements of the procedure and stimuli were standardised. These common elements will be outlined in this chapter.

2.1 General Structure of Stimuli: The 'ABA-' test sequence

The 'A' and 'B' tones in 'ABA-' triplets were arranged in one of two ways, as shown in Figure 2.1. Either the 'A' tone was fixed at a lower frequency than the 'B' tone, in which case the triplet was set in a 'LHL-' (Low-High-Low) configuration, or the 'A' tone was fixed at a higher frequency than the 'B' tone, in which case the triplet had a 'HLH-' arrangement. The selection of triplet configuration depended on the factors/properties being investigated. In some experiments, both configurations were used to explore the influence of triplet structure on build-up and resetting. The frequency separation between 'A'and 'B' tones, termed Δf, was determined on the basis of pilot studies to minimise the influence of ceiling and floor effects, whilst allowing scope for observation of any interactions between frequency separation and condition.

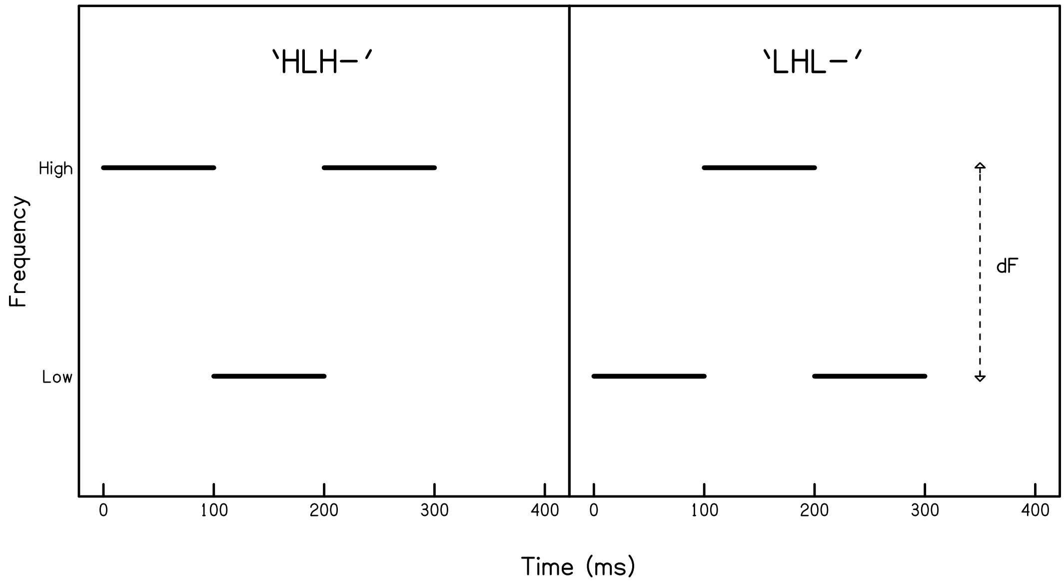

FIGURE 2.1: Structure of 'HLH' and 'LHL' triplets. Each tone, and the silence has has a duration off 100 ms. The high and low tones are separated by a ΔF of either 4, 6 or 8 semitones.

Regardless of triplet configuration, stimuli for all experiments were created with 'A'- and 'B'-tone separations of 4, 6 and 8 semitones (cf. Haywood and Roberts, 2013, Experiment 3, which used 3, 6, and 9 semitones). In each experiment, the frequency of one subset was kept constant whilst the other was varied according to Δf.

2.2 Apparatus and Stimulus Parameters

Stimuli were synthesised using Mitsyn (Henke, 1997). Aside from the ITD experiment (see Chapter 3), where sequences were synthesised at a sampling rate of 40 kHz, all experimental stimuli were made with a sampling rate of 20 kHz and saved to disk. The stimuli were presented via a Sound Blaster X-Fi HD sound card (Creative Technology, Singapore) over Sennheiser HD480-II headphones.

The programmable attenuator (Tucker-Davis Technologies PA5, Alachua, Florida) was used to set the overall output level, which was calibrated using a sound-level meter (Brel & Kjaer, type 2209) coupled to the earphones by an artificial ear (type 4153). Participants were able to view their progress on screen throughout the experiment and recorded their current percept using the keyboard. Experiments were run using a program designed with the Visual Basic programming language (Visual Studio, 2010, version 10.0) incorporating DirectX. Listeners completed the experiment in a single-walled chamber (Industrial Acoustics 401A) housed within a quiet room.

2.3 Sequence Structure

For the first two experimental chapters, the continuous assessment procedure (as first used by Anstis and Saida (1985) was used for examining the effects of abrupt and of gradual changes in sequence properties on the build-up and resetting of auditory streaming. Inducer experiments were primarily aimed at examining hysteresis effects, i.e., the ability of a prior percept to bias the current percept (Rogers and Bregman, 1993, 1998).

2.3.1 Continuous assessment

Listeners were required to continually monitor and record their percept (using the keyboard) throughout the duration of the test sequence. Listeners were instructed to press 'A' when they heard the sequence as integrated (single stream) or to press 'L' when hearing it as segregated (two streams). In cases where the percept was ambiguous, listeners were asked to report the most dominant percept. Listeners were required to record their percept as soon as the test sequence began, and every time it changed thereafter.

2.3.2 Inducer-Test Sequence Setup

Induction experiments used sequences comprising a 2-s induction sequence followed by a standard test sequence (the length of which varied between experiments). At the boundary between the inducer and the test sequence, the on-screen message presented to participants changed from 'Please Wait' to 'Please Respond'. The use of an inducer was intended primarily to investigate hysteresis effects, i.e., the ability of a previous percept to bias the auditory system. Listeners were instructed not to respond during the inducer sequence until the message read 'Please Respond', at which point they should respond as for the continuous assessment procedure.

2.4 General Procedure

Each condition within an experiment was presented 10 times (once in each block) in a randomised presentation order. In the case of sequences involving ITD cues, 5 repetitions were used for each lateralisation these could then be combined for analysis after screening to check for any asymmetrical effects. Participants were able to take a comfort break between blocks.

The loudness inducer pilot experiment was run using neutral instructions for 6 listeners and TCB for 6 listeners. It was noted that in addition to the expected lower overall segregation level, TCB data was much 'noisier' with less consistency than the data derived using neutral instructions. It seems likely that this results from fluctuations in the ability of listeners to maintain their focus on fulfilling these instructions, which requires more effort than neutral listening.

It is worth noting that TCB instructions are typically used only for one-off judgements (Rogers and Bregman, 1993, 1998). van Noorden (1975) also asked listeners were asked to 'hold together' their percept whilst adjusting the Δf to determine the TCB. Studies using continuous assessment of sequences (e.g. Anstis and Saida, 1985) typically use neutral instructions. It was therefore decided that neutral instructions were more appropriate in this study, as the 'noise' resulting from issuing TCB instructions could render more subtle effects undetectable. Listeners were therefore instructed to report their percept, not favouring any in particular. In cases where the percept was ambiguous, listeners were instructed to select the dominant one.

Each condition was presented to participants interspersed by short intervals to allow the decay of any build-up that might have occurred. As it is generally agreed that decay is near-complete at approximately 4-s (Beauvois and Meddis, 1997; Bregman, 1978b; Cusack et al., 2004), the silent intervals between conditions were 5-s long to minimise any bias of the previous sequence on any subsequent sequences.

2.5 Participants: recruitment and training

Each experiment included data from 12 participants, recruited mainly from the Aston University Student population. They were required to have no known hearing loss and were screened in line with BSA (2012) protocols for Pure Tone Audiometry to identify any participant with a hearing impairment of which they were unaware. Participants with thresholds exceeding 20 dB HL at 0.5, 1, 2 or 4 kHz were excluded from the study. After reading the instructions issued, their understanding was confirmed verbally prior to completing a 'training block' identical to the test conditions. A second training block was offered but rarely required by listeners. Presenting conditions at Δfs of 4, 6 and 8 ST, not only provided information on the interaction between frequency separation and condition but as the effect of frequency separation has been confirmed in previous studies, it also provided criteria for exclusion. If participants did not show a systematic effect of frequency separation on judgments of stream segregation, they were excluded from the study. This happened in only a few cases.

2.6 Data Processing

The response period was divided into 'time-bins' of either 1.0 s (i.e 0-1 s, 1-2 s etc.) or 1.2 s (i.e. 0-1.2s, 1.2-2.4s etc.), as appropriate (see the descriptions of each experiment for further details). For each time-bin, the proportion of time that the listener reported a segregated percept was calculated using the precision timings from the key-press data, providing a measure of segregation level (%) for each time-point. By using time-bin lengths of 1.0 or 1.2-s, adequate temporal resolution was obtained whilst smoothing out any fluctuations resulting from variability in the key-press timings.

For each time-bin, responses were included only if listeners had already responded prior to the current time-bin or responded within the first 0.5-s of the current time-bin. For each listener and condition, the data was averaged across trials for each time-bin. As found by Haywood and Roberts (2013), very few responses were recorded from the first time-bin (0-1s). Therefore responses made during the first time-bin were used only for the purpose of calculating the duration of a segregated percept in the subsequent time-bin; they were not included in the analysis or graphical representation of the data.

Where relevant the pairwise comparisons of time interval have been kept in the main text of this thesis although from Chapter 4 onwards, they are largely accessible in the Appendix. All error bars presented indicate inter-subject standard error, and significant terms within the summary tables are shown in bold font.

Chapter 3

Gradual and Abrupt Changes in Frequency and Location

3.1 Introduction

The experiments presented within this chapter investigated the effect of changing stimulus properties on the build-up of stream segregation. Sudden shifts within gradually changing sequences were used to establish if abrupt changes could have a resetting effect when presented in the context of continuously varying sequences. Previous studies have usually examined the resetting effect of an abrupt change using sequences with otherwise constant stimulus properties (Roberts et al., 2008; Haywood and Roberts, 2010), but listeners are often exposed to sounds that change gradually and abruptly. By introducing both gradual and abrupt changes across a range of values to produce substantial shifts in pitch and lateralisation, the differing effect of changes in frequency and ITD can be observed. Experiments 1 and 2 therefore explored the effects of changing base frequency (whilst preserving A-B frequency separation in semitones) and ITD, respectively, using continuous assessment of the streaming status of 20-s 'ABA-' triplet sequences.

The effects of abrupt and gradual change were systematically investigated by Rogers and Bregman (1998), who used an inducer-test setup to explore the effect of changes in source location and level. The inducer was a 4.8-s sequence with a subsequent 1.2-s test sequence. For the abrupt-change case, the fixed properties of the inducer changed at the inducer-test boundary to those of the standard test sequence. The properties of the gradually changing inducer began distinctly differently from those of the test sequence, but changed continuously so that at the inducer-test boundary they were approaching those of the constant test sequence. At the end of each trial, listeners were requested to provide a one-off judgement of the extent of stream segregation using a scale (1-8, where 1 corresponded to entirely segregated and 8 to entirely integrated). On the basis of the response to a given trial, the 'A-B' frequency separation of the subsequent trial was adjusted (up or down) to make the percept increasingly ambiguous. Through an iterative process, this would provide a measure of the border between segregation and integration in terms of the 'A-B' separation in semitones.

Rogers and Bregman (1998) investigated the influence of ITD and ILD cues separately, in addition to the combination of sound localisation cues generated by free-field presentation of the sounds over loud speakers. In the case of ITD changes, both standard (steady) and gradual-change inducers had a similar influence; the test sequences that followed had the lowest segregation boundaries. This lower threshold for segregation was attributed to the build-up of streaming which had occurred in response to the inducer continuing for the test sequence. Sudden changes in lateralisation from either centre-to-left or right-to-left at the inducer-test boundary significantly elevated the 'A-B' frequency separation required to elicit segregation in the subsequent test sequence. The findings of Roberts et al. (2008), who measured temporal discrimination thresholds as a proxy for integration, were largely consistent with the findings of Rogers and Bregman (1998). The regular test sequences induced increasing temporal discrimination thresholds as a result of build-up. As expected, abrupt changes in lateralisation resulted in maximal resetting, indicated by improved 'B'-tone delay detection.

As discussed in the introductory chapter, investigations into the effect of abruptly changing stimulus properties have been fairly limited. In most cases, the experimental procedure involved an inducer-test setup where inducer properties were systematically varied whilst the properties of the test sequence remained fixed (Rogers and Bregman, 1998; Haywood and Roberts, 2010). A limitation of this procedure is that it provides relatively little information on the percept prior to any change, as only the influence of the inducer on the perception of an (often brief) test sequence is directly assessed. Additionally, the potential influence of non-acoustic markers of the inducer-test sequence boundary (such as a change in the visual display) on the test sequence percept, cannot be dismissed altogether.

Despite these limitations, the results of the inducer-test experiments by Rogers and Bregman (1998) were largely consistent with an objective study by Roberts et al. (2008), particularly with respect to lateralisation cues. It is notable that Roberts et al. (2008) did not use an alternating-frequency inducer. Rather, they used a 2-s fixed frequency inducer (equivalent to a repeating L-tone sequence), followed by a 0.6-s test sequence (consisting of repeating 'HLHL...' tones). The lateralisation of the sequence was shifted to the opposite ear at the inducer-test boundary. The temporal discrimination task used required listeners to discriminate the relative timing of subsequent tones in the sequence. The detection of a delay in the sequence was better when the percept was more integrated. Roberts et al. (2008) noted that in the case of abrupt changes in lateralisation the threshold for delay detection remained low (even as the Δf_{AB} was increased) indicating that a sudden shift in lateralisation limited the transfer of build-up from the inducer to test sequence. However, it has been suggested that—unlike an alternating-frequency inducer—a constant frequency inducer increases subsequent stream segregation by capturing a subset of tones in the test sequence rather than elevating the rate of build-up (cf. Bregman and Rudnicky, 1975). Therefore it could be that improved delay discrimination following an abrupt change in lateralisation results from a disruption of capture rather than resetting or the failure to transfer of build-up. Nonetheless, these results are largely consistent with those of Rogers and Bregman (1998) which suggests that resetting in response to abrupt changes observed in the context of inducer-test setups can be replicated using other indirect measures of streaming.

This loss of stream segregation following an abrupt change has also been noted in the context of shifts in frequency. Anstis and Saida (1985) explored the effect of frequency region using a pure tone that they described as frequency-modulated by a square wave (i.e., equivalent to an alternating 'ABAB...' sequence). A 4-s fixed-property adaptation sequence with centre frequency of 1 kHz, and of 2 ST modulation depth (corresponding to the frequency separation between the tone subsets) was presented prior to a 1-s test sequence. The centre frequency of the test sequence varied from trial to trial (between 1 octave lower and higher than that of the adapting sequence). Initially the test sequence was presented at the same rate as that of the adapting sequence (TRT

= 125 ms), but the stimulus was constantly adjusted, using a nulling procedure, to be at the perceptual borderline between coherence and segregation. On each trial, this presentation of adapting and test sequences was alternated continuously for 90 s. The mean nulling rate over the last 30-s was recorded as a measure of the segregation boundary for each condition. It was noted that maximal adaptation occurred at 1 ST above that of the centre frequency of the adapting sequence; i.e., the lowest nulling rate (longest TRT) that was required to reach the segregation boundary. In general, there was clear evidence of adaptation within the -1 to +3 ST range (the asymmetry was not accounted for). Outside of these boundaries, the adaptation effect was extinguished; i.e., a change at the boundary between the adapting and test sequences outside this range resulted in a near-complete loss of build-up or resetting of segregation.

Given that build-up is a dynamic process, it would be useful to obtain a measure of how listeners perceive continuously changing stimuli over the course of an entire sequence. This is particularly important when considering what little is known about the time course of resetting effects or the influence of the extent and direction of an abrupt change on the duration of any consequent resetting. Previous studies examining the effect of either abrupt or gradual changes have typically used an inducer-test setup, which has had a number of implications for our understanding of the effect of changing stimulus properties. Firstly, this has meant that there is no direct report of the percept before and during, as well as after, the introduction of an abrupt change. This has limited our understanding of the nature of resetting; is it really that the process of build-up restarts or, alternatively, is there a failure of pre-existing build-up transferring from an inducer to the test sequence? Secondly, in most cases a relatively short inducer (4-s or less) has been used, with the total sequence duration remaining under 6-s (Rogers and Bregman, 1998; Roberts et al., 2008), which limits the scope of build-up prior to introduction of a change. Thirdly, despite van Noorden (1975) using continuous monitoring of changing sequences, no-one has yet investigated the effect of abrupt changes within continuously varying sequences. It could be argued that Anstis and Saida (1985) used continuous monitoring of longer sequences, but (as discussed later in this chapter) the 'nulling' procedure provided a measure of streaming that is not directly comparable with the continuous assessment method used here.

The differences between the influence of abrupt and gradual changes on streaming can be considered in the context of the 'evidence accumulation' account of build-up.

Bregman (1978) suggests that, as perceptual systems appear to be biased towards undifferentiated perceptions, the auditory system requires time to build-up evidence before interpreting a single auditory input as being produced by two distinct and independent sources. An abrupt change could therefore signal a new sound event, restarting the evidence-accumulation process and returning to the single-percept bias.

This account remains fairly consistent with the existing evidence on the effect of abrupt changes, but explaining the effect of gradual change in this context is not quite as simple. Rogers and Bregman (1998) propose two accounts for the comparable levels of segregation induced by the standard case and by the gradually changing sequences, both of which are consistent with the evidence-accumulation account of build-up. The first is that the small, continuous changes in a sequence are considered to be the gradually changing properties of sounds originating from a single source and thus favouring cumulative induction of a streaming percept. The second is that, as the properties of the gradually changing sequence are brought closer to those of the subsequent test sequence, they overlap increasingly with the frequency region sampled by the evidence accumulation process centred on the test sequence. This results in the build-up of segregation continuing over the inducer-test boundary.

The multi-second neural adaptation model (Micheyl et al., 2005; Pressnitzer et al., 2008) does (to some extent) provide a plausible neural basis for the evidence accumulation account of build-up. Based on responses to pure-tone sequences, those authors suggest that build-up is a by-product of the decay in the response magnitude of frequency-tuned neural responses as observed in the primary auditory cortex of rhesus macaques (Micheyl et al., 2005) and the cochlear nucleus of guinea pigs (Pressnitzer et al., 2008). In both cases, they note a habituation of neural responses following a similar time-course to the build-up observed from psychophysical data. More specifically, Pressnitzer et al. (2008) suggest that this 'slow-gain control' of neural responses results from a long-term synaptic depression and fast recovery of peripheral neurons that potentially could be modulated by descending projections of the medial olivo-cochlear efferent system. In accordance with this neural account of build-up, abrupt changes which stimulate different neural populations could reset this process.

Whilst this would provide a plausible account for build-up and resetting in the case of stimulus properties with different excitation patterns—e.g., an abrupt change in the centre frequency of a sequence of alternating pure tones—it does not explain the evidence that abrupt changes in location (cued by ITD in addition to ILD) can reset build-up (Rogers and Bregman, 1998). The efferent connections noted by Pressnitzer et al. (2008) suggest modulation of this process by higher-level decision making. Efferent modulation of responses, due to the auditory systems recognition of an abrupt change indicating the presence of a new, distinct stimulus could briefly increase the magnitude of the neural responses—translating to an increased perception of the stimulus as segregated. However, there is limited evidence of this from physiological studies, and so this suggestion is still speculative.

Experiments 1 and 2 aimed to establish whether changes in base frequency and ITD (both abrupt and gradual) have comparable effects on build-up and resetting of stream segregation. The direction and extent of these changes in sequence properties were varied to further establish whether the magnitude of a change affects the degree to which a percept was 'reset' and the duration of this resetting effect. Experiment 1 investigated the effect of changes in base frequency, a feature that strongly affects the excitation pattern elicited by a stimulus. Lateralisation, cued by ITD, however, is processed at the brainstem level and above, and changes in ITD do not introduce peripheral excitation-pattern cues. Therefore, Experiment 2 used changes in ITD to establish the influence of changes in the perceived lateralisation of a sound source on the build-up of streaming, without modifying the excitation pattern of the stimulus.

3.2 Experiment 1: Gradual and abrupt changes in frequency

3.2.1 Method

The general method and procedure for this experiment is described in Chapter 2. This experiment used a continuous assessment method to establish the effects of changes in base frequency over the duration of a 20-s 'ABA-' sequence.

3.2.2 Conditions and Hypothesis

During the test sequence the frequency of the tones could either remain fixed throughout, gradually ascend/descend, or gradually change with an abrupt rise/fall midway through the sequence. The specified frequency separation of the 'A' and 'B' tones was maintained throughout the course of the test sequence. In the gradual-change conditions the frequency of the 'A' tone either ascended or descended between the minimum (500 Hz) and maximum frequency (1 kHz) positions, changing direction at the 10-s point. Abrupt-change conditions began by following the same trajectories as the gradual change cases, but at 10-s the 'A' and 'B' tones were transposed in frequency (by either ±12, ±6, or ±3 ST). This permitted the extent of any resetting effect to be compared across different magnitudes of base frequency shift. The choice of an abrupt change of 3 ST or greater was made despite Anstis and Saidas (1985) finding that a 1 ST shift was sufficient to abolish the increase in segregation otherwise caused by the adaptor. This is because, in the current experiment, the abrupt change was occurring within a sequence whose centre frequency varied continuously at a rate of 0.5 ST/triplet. This range of values was informed by pilot work, which indicated that larger frequency shifts were required to cause loss of build-up for a sequence continuously varying at this rate, and by consideration of the limitations in the design of Anstis and Saidas study (see discussion for Experiment 1). To avoid confusion, the frequency separation of 'A' and 'B' tones is referred to as Δf_{AB}. The abrupt change in base frequency (where the difference between 'A' and 'B' tones remains the same) is referred to as a 3-, 6-, or 12-ST shift in base frequency.

The effect of base frequency on stream segregation has been studied in the context of sequences with fixed properties and, in general, it has been observed that higher base frequencies have either no influence or only slightly increase the tendency to hear segregation. The initial investigation by Miller and Heise (1950) using pure-tone sequences suggested that the FB was approximately 15% of signal frequency until 1 kHz ($\Delta f/f = 0.15$), but Shonle and Horan (1976) found that the FB was approximately 0.25 of the corresponding critical band, suggesting a close relationship with frequency resolution in the periphery. Subsequent investigations across a wide range of frequencies indicate that the FB is approximately 0.4 times the equivalent rectangular bandwidth (ERB) (Rose and Moore 1997, 2000, 2005). Altogether, these outcomes would suggest little effect of base frequency on degree of segregation in the range of base frequencies used in this experiment (A=500 Hz - 1 kHz).

If any change were to be observed, it would be expected that there would be a slightly increased tendency for segregation at higher frequencies within this range, owing to narrower auditory filter bandwidths resulting in improved frequency resolution on a log scale. The conditions listed below are summarised in Figure 3.1. Each condition was presented with a Δf_{AB} of 4, 6, and 8 ST.

1. *Fixed base-frequency - max:* sequence at maximum base frequency (1 kHz).

2. *Fixed base-frequency - min:* sequence at minimum base frequency (500 Hz).

3. *Ascending-first, Gradual Change:* Ascending frequency at a rate of 0.5 ST/triplet until the base frequency reaches 1 kHz (triplet 25 at 9.6-s), before changing direction and descending (triplet 26 at 10-s). Rather than changing direction, the final triplet (50) continues to fall and has a base frequency of 486 Hz (this value is 0.5 ST below the nominal minimum, but the final triplet is too late to have any appreciable effect on responses).

4. *Descending-first, Gradual Change:* Descending frequency at a rate of 0.5 ST/triplet until the base frequency reaches 500 Hz (triplet 25 at 9.6-s), before changing direction and ascending (triplet 26 at 10-s). Rather than changing direction, the final triplet (50) has a base frequency of 1029 Hz (this value is 0.5 ST above the nominal maximum, but the final triplet is too late to have any appreciable effect on responses).

5. *Ascending-first, Abrupt Fall 1:* As for the gradual-change case until 10s (triplet 26), at which point the base frequency abruptly falls to 500 Hz (12 ST decrease) from where it ascends gradually at the standard rate (0.5 ST per triplet) to 1 kHz (triplet 50).

6. *Ascending-first, Abrupt Fall 2:* As Condition 4, but base frequency abruptly falls to 707 Hz (6 ST decrease), then ascends gradually to 1 kHz (triplet 38 at 14.8-s) after which it descends gradually to 707 Hz (triplet 50).

7. *Ascending-first, Abrupt Fall 3:* As Condition 4, but base frequency abruptly falls to 841 Hz (3 ST decrease), then ascends gradually to 1 kHz (triplet 32 at 12.4-s) after which it descends gradually to 595 Hz (triplet 50).

8. *Descending-first, Abrupt Rise 1:* Descending frequency at a rate of 0.5 ST/triplet from 1 kHz until the base frequency reaches 500 Hz (triplet 25 at 9.6-s). At 10s

(triplet 26), the base frequency abruptly rises to 1 kHz (12 ST increase) from where it descends gradually, as previously, to 500 Hz (triplet 50).

9. *Descending-first*, *Abrupt Rise 2:* As Condition 8, but base frequency abruptly rises to 707 Hz (6 ST increase), and then descends gradually to 500 Hz (triplet 38 at 14.8-s) after which it ascends to 707 Hz (triplet 50).

10. *Descending-first*, *Abrupt Rise 3:* As Condition 8, but base frequency abruptly rises to 595 Hz (3 ST increase), and then descends to 500 Hz (triplet 32 at 12.4-s) after which it ascends to 841 Hz (triplet 50).

The fixed base-frequency cases would be expected to elicit fairly similar patterns of build-up, as the 500 Hz and 1 kHz cases have broadly comparable ERBs. However, in principle, a slightly greater extent of segregation might be expected for the 1-kHz base frequency case owing to a small decrease in the overlap of excitation patterns between tone subsets relative to the 500-Hz case. Consistent with a peripheral channelling account of streaming, the influence of gradual change cases on the build-up of streaming should be limited, as a small change in base frequency of 0.5 ST would be within the adapting region identified by Anstis and Saida (1985). Even so, the 0.5 ST shift every triplet may have a small, but repeated resetting effect leading to an appreciable slowing of build-up. Furthermore, the correlated A-B changes over time may themselves cue a common origin for the two subsets of tones, reducing the tendency for segregation. According to the evidence-accumulation hypothesis, near-complete resetting would be expected in response to any salient perceptual change, as is evident in the Anstis and Saida (1985) data.

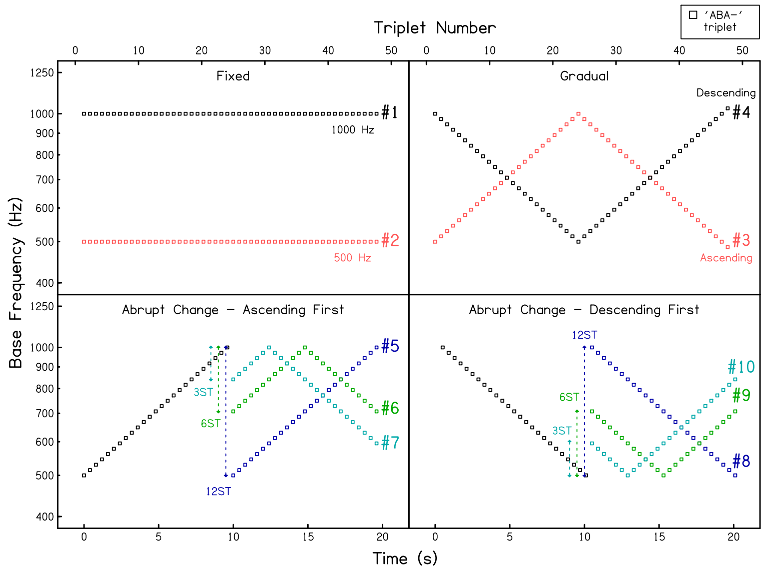

FIGURE 3.1: Illustration of the conditions in Experiment 1. The panels show the trajectory of base frequency changes for constant, gradual and abrupt-change conditions over the course of a 20-s test sequence. Each triplet is denoted by a single square.

3.2.3 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As described in Chapter 2, all conditions were presented during each of the 10 blocks, which were split over 2 testing sessions.

3.2.4 Results

3.2.4.1 Effects of Δf_{AB}, Condition and Time Interval

The effects of fixed, gradual, abrupt ascending, and abrupt descending cases were compared using four, three-way within-subjects ANOVAs, where the three factors were Condition, Δf_{AB}, and Time Interval. The outcomes of each ANOVA are laid out in a table; for ease of reading, only the p-values are quoted in the main body of the text. The first ANOVA (see Table 3.1) explored the effect of baseline frequency and so was restricted to the two fixed base-frequency conditions (500 Hz vs. 1 kHz). The second (see Table 3.3) compared the combined fixed cases (mean of 500-Hz and 1-kHz conditions) with the combined gradual cases (mean of gradual-ascending and -descending conditions). When combined, the fixed and gradual cases shared the

Table 3.1: Three-way repeated measures ANOVA comparing fixed base-frequency cases only (maximum and minimum base frequencies.)

Factor	*dF*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**34.796**	**<0.001**	**0.760**
Condition (Maximum vs. Minimum Base Frequency)	(1,11)	1.981	0.227	0.130
Time Interval	**(18,198)**	**19.467**	**<0.001**	**0.641**
Δf_{AB} × Condition	(2,22)	0.866	0.435	0.073
Δf_{AB} × Time Interval	(36,396)	0.432	0.999	0.038
Condition × Time Interval	(18.198)	1.398	0.135	0.113
Δf_{AB} × Condition × Time Interval	(36,396)	1.298	0.122	0.106

Table 3.2: Pairwise comparisons of A-B frequency separations for fixed base-frequency cases (only 4 ST vs 6 and 8 ST, and 8 ST vs 4 and 6 ST are shown.)

Δf_{AB} (ST)		Mean Difference (%)	*p*
4	**6**	**17.1**	**<0.001**
	8	**-31.8**	**<0.001**
8	**4**	**31.8**	**<0.001**
	6	**14.7**	**0.002**

Table 3.3: Three-way repeated measures ANOVA comparing fixed base-frequency (mean of maximum and minimum) and gradual change cases (mean of ascending and descending.)

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**40.183**	**<0.001**	**0.788**
Condition (Fixed vs. Gradual)	(1,11)	0.912	0.360	0.077
Time Interval	**(18,198)**	**22.400**	**<0.001**	**0.671**
Δf_{AB} × Condition	(2,22)	22.551	0.101	0.188
Δf_{AB} × Time Interval	(36,396)	0.929	0.590	0.078
Condition × Time Interval	(18,198)	0.745	0.761	0.063
Δf_{AB} × Condition × Time Interval	(36,396)	0.614	0.963	0.053

same mean base frequency, so that any difference between cases could be assumed to result from the gradual change. The third (Table 3.5) and fourth (Table 3.7) ANOVAs compared the effect of abrupt changes on the time-bins from 11-s onwards, for initially ascending and initially descending conditions with the corresponding gradual change only cases, respectively. Taking typical listener reaction times into account, the 11-12 s time bin is the first interval for which any effect of an abrupt change would be apparent. Tables 3.2, 3.4, 3.6 and 3.8 include the pairwise comparisons associated with each of these ANOVAs.

For each Δf_{AB} tested, the fixed conditions at maximum and minimum baseline

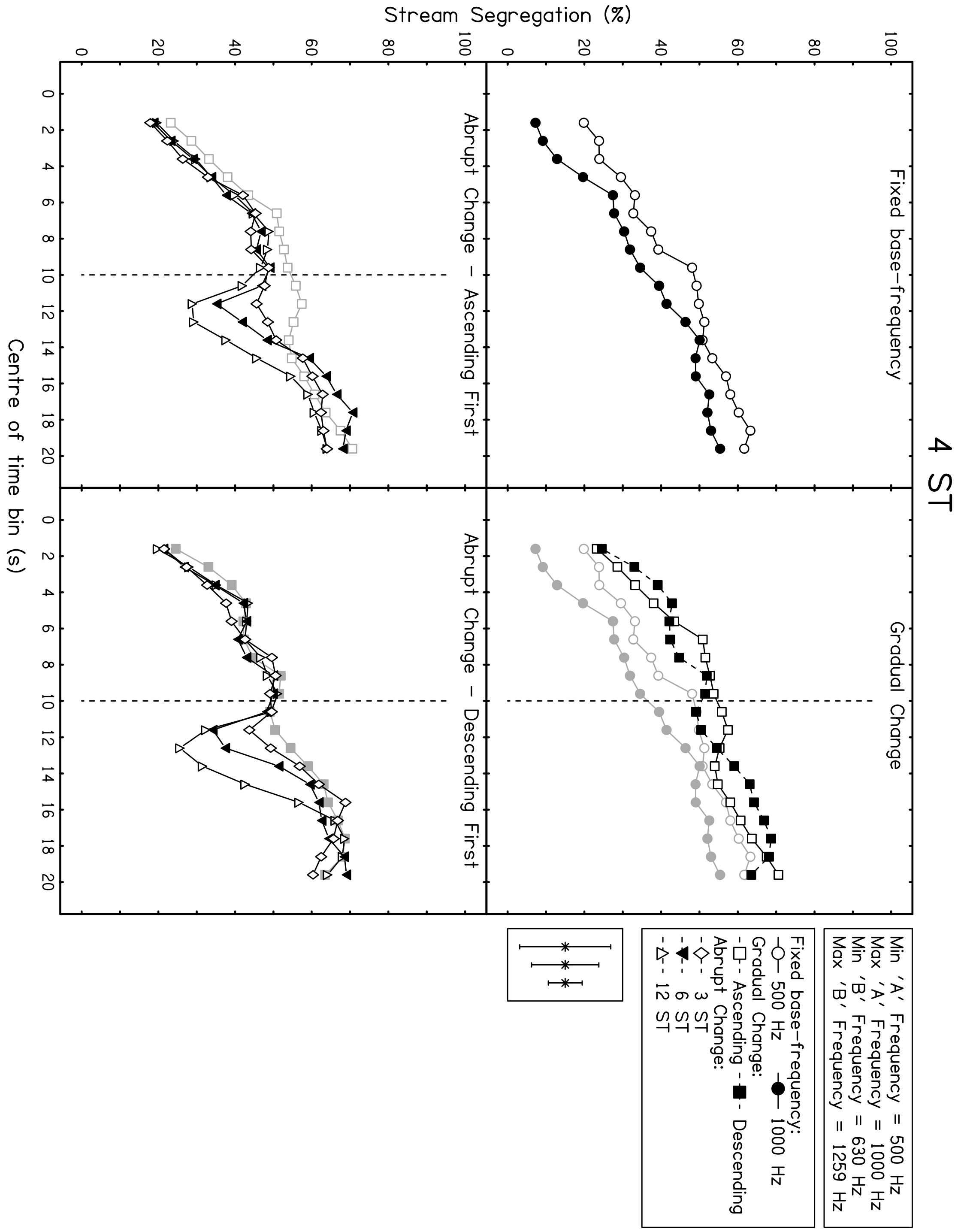

FIGURE 3.2: The stream segregation data averaged across listeners from Experiment 1 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition. For ease of comparison, the constant reference cases are repeated in grey in the top-right panel, the gradual change - ascending first case in the bottom-left panel, and the gradual change - descending first case in the bottom-right panel.

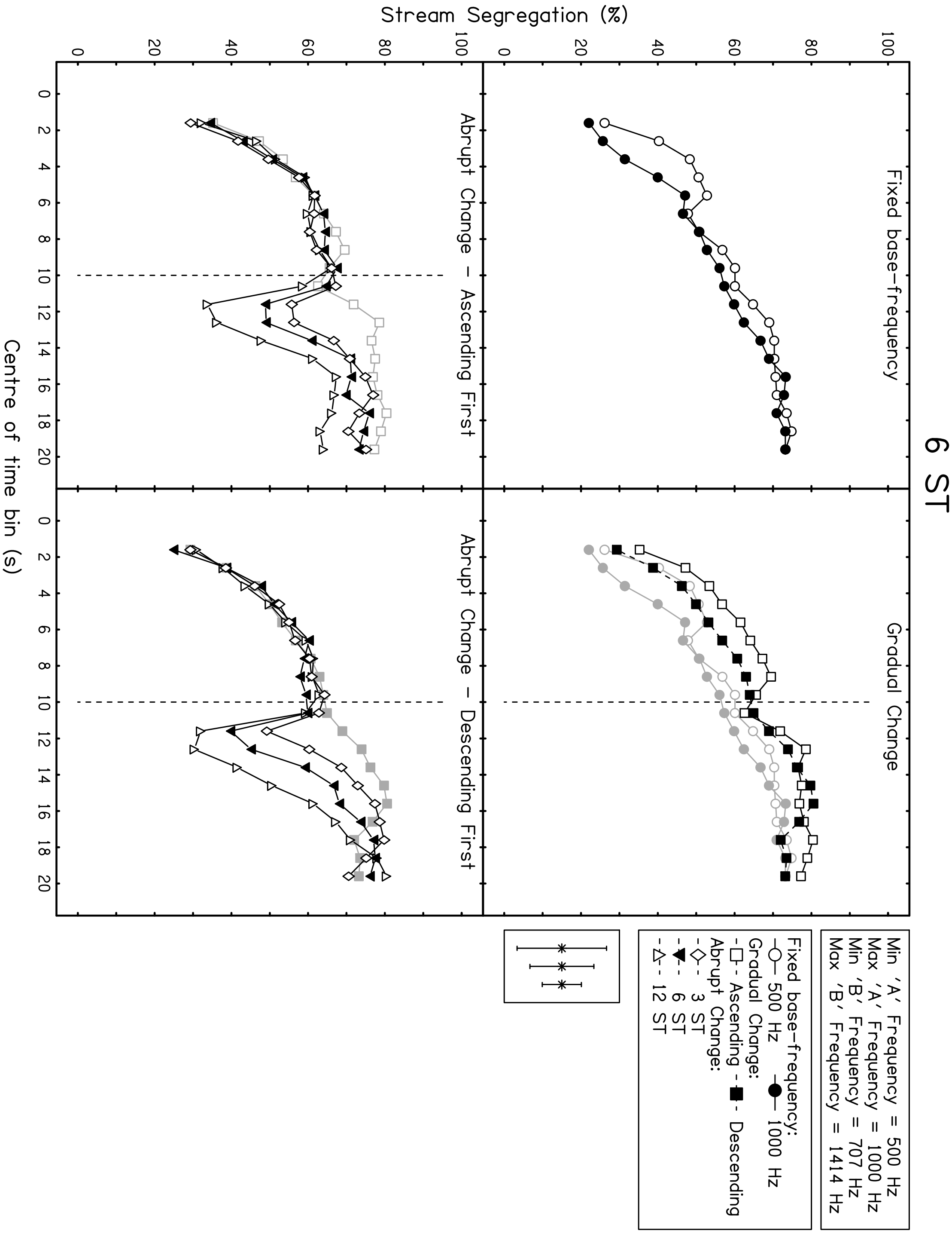

FIGURE 3.3: The stream segregation data averaged across listeners from Experiment 1 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition. For ease of comparison, the constant reference cases are repeated in grey in the top-right panel, the gradual change - ascending first case in the bottom-left panel, and the gradual change - descending first case in the bottom-right panel.

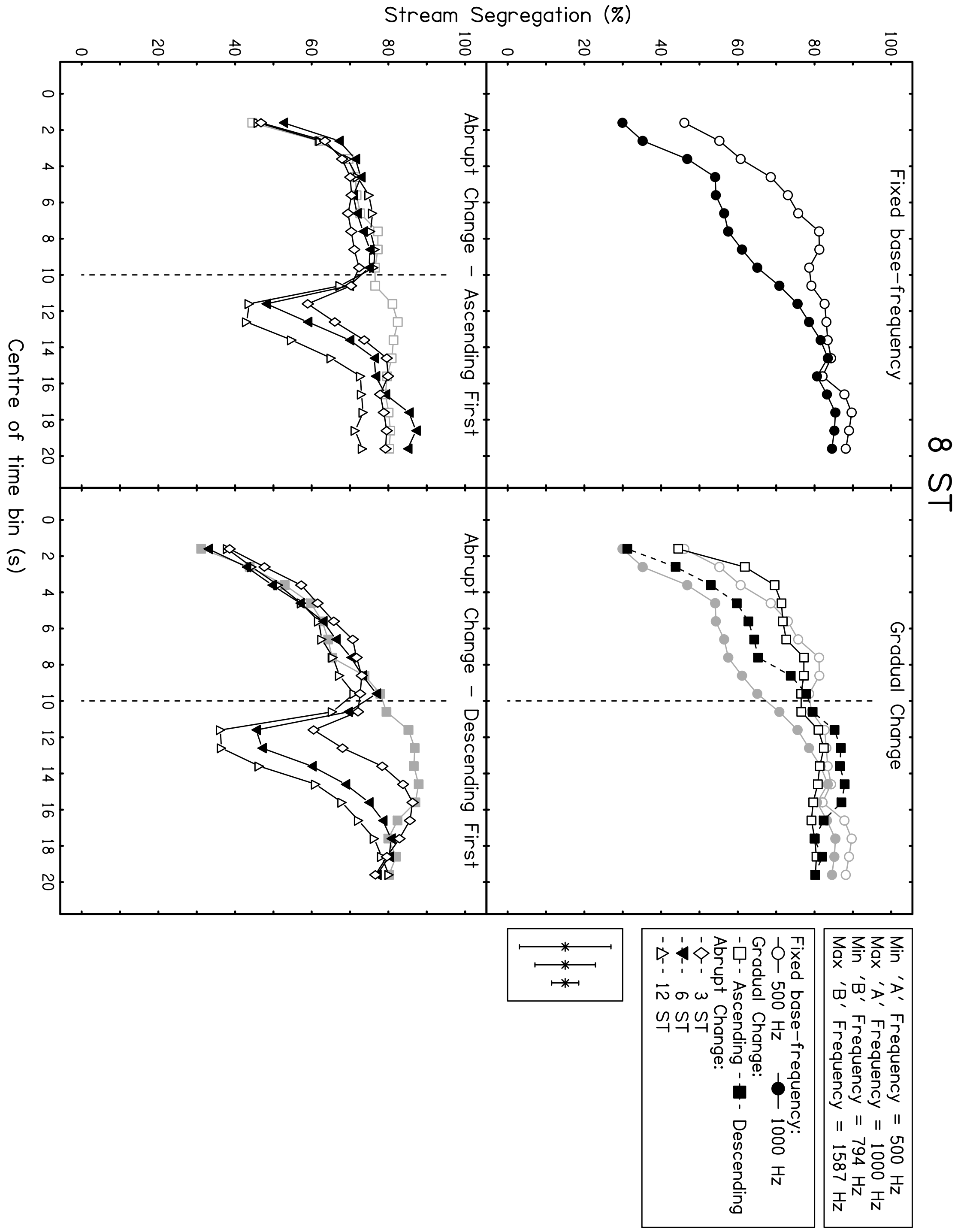

Figure 3.4: The stream segregation data averaged across listeners from Experiment 2 displaying the pattern of build-up over the 20-s test sequence fora Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition. For ease of comparison, the constant reference cases are repeated in grey in the top-right panel, the gradual change - ascending first case in the bottom-left panel, and the gradual change - descending first case in the bottom-right panel.

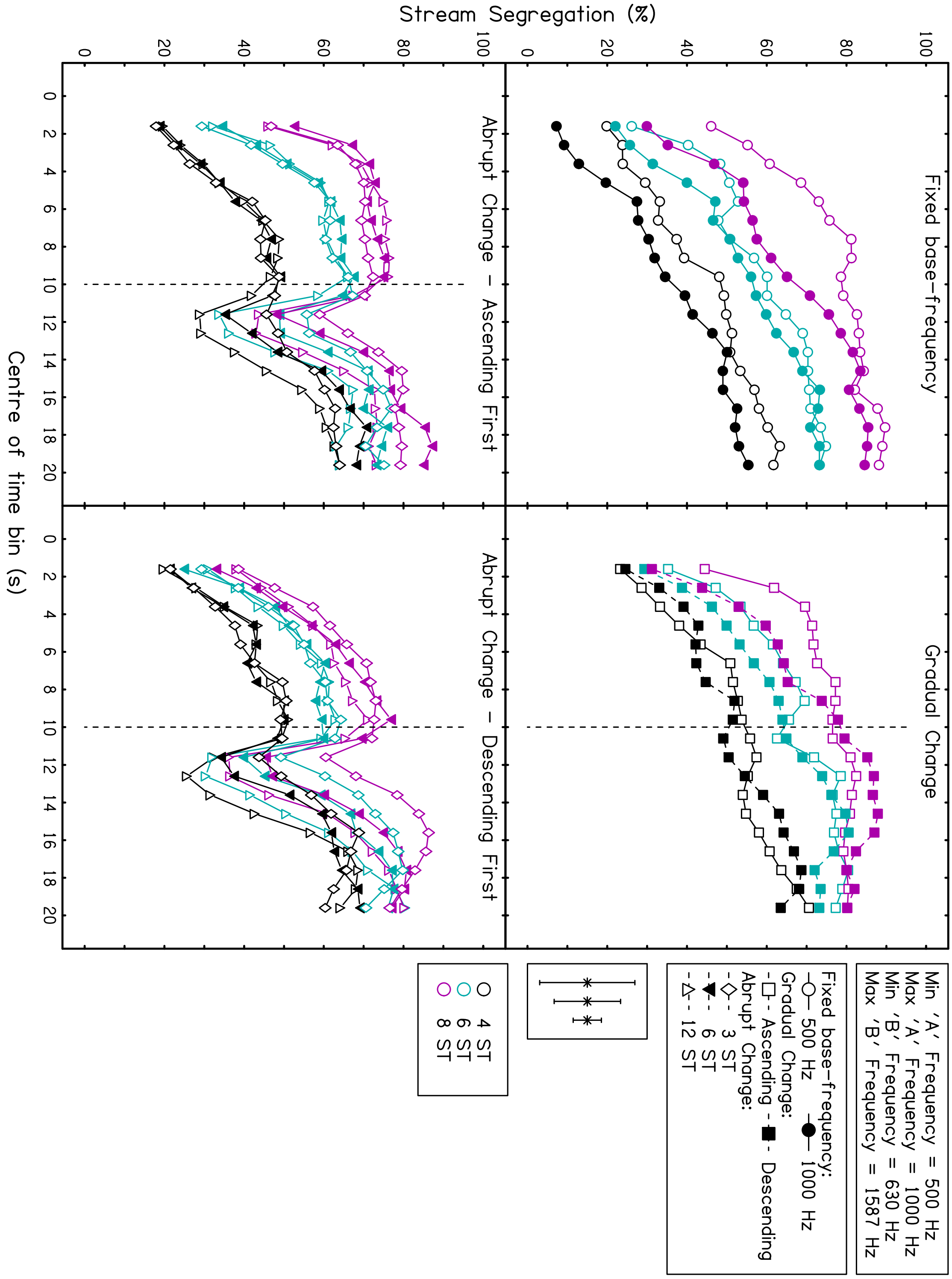

Figure 3.5: Summary of stream segregation data from Experiment 1, displaying the pattern of build-up for 4, 6, and 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

Table 3.4: Pairwise comparisons of time interval (1-2 s vs all other time intervals and 19-20 s vs all other time intervals) derived from fixed base-frequency cases.

(I) Time_Interval	(J) Time_Interval	Mean Difference (I-J)[%]	Std. Error	*p*
1-2	**2-3**	**-6.3**	**0.014**	**0.001**
	3-4	**-12.1**	**2.6**	**0.001**
	4-5	**-18.5**	**3.8**	**0.001**
	5-6	**-22.8**	**4.6**	**<0.001**
	6-7	**-22.7**	**5.3**	**0.001**
	7-8	**-26.1**	**5.5**	**0.001**
	8-9	**-28.6**	**5.4**	**<0.001**
	9-10	**-31.9**	**6.1**	**<0.001**
	10-11	**-34.2**	**7.1**	**0.001**
	11-12	**-37.2**	**7.2**	**<0.001**
	12-13	**-39.9**	**7.5**	**<0.001**
	13-14	**-42.0**	**7.5**	**<0.001**
	14-15	**-43.0**	**7.6**	**<0.001**
	15-16	**-43.6**	**7.4**	**<0.001**
	16-17	**-45.7**	**7.0**	**<0.001**
	17-18	**-46.8**	**7.0**	**<0.001**
	18-19	**-47.9**	**7.0**	**<0.001**
	19-20	**-47.5**	**7.2**	**<0.001**
19-20	**1-2**	**47.5**	**7.2**	**<0.001**
	2-3	**41.2**	**7.7**	**<0.001**
	3-4	**35.4**	**6.6**	**<0.001**
	4-5	**29.0**	**7.0**	**0.002**
	5-6	**24.7**	**6.9**	**0.004**
	6-7	**24.9**	**.4**	**0.001**
	7-8	**21.4**	**5.3**	**0.002**
	8-9	**18.9**	**4.8**	**0.002**
	9-10	**15.6**	**4.8**	**0.008**
	10-11	**13.3**	**4.5**	**0.013**
	11-12	**10.4**	**3.9**	**0.022**
	12-13	**7.6**	**3.3**	**0.045**
	13-14	5.5	3.0	0.096
	14-15	4.5	3.4	0.213
	15-16	3.9	2.6	0.162
	16-17	1.8	1.8	0.337
	17-18	0.7	1.5	0.65
	18-19	-0.4	1.0	0.707

TABLE 3.5: Three-way repeated measures ANOVA comparing gradual and abrupt change ascending-first cases.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**17.987**	**<0.001**	**0.621**
Condition	**(3,33)**	**4.843**	**0.007**	**0.306**
Time Interval	**(8,88)**	**12.329**	**<0.001**	**0.528**
Δf_{AB} × Condition	(6,66)	0.986	0.442	0.082
Δf_{AB} × Time Interval	(16,176)	1.592	0.075	0.126
Condition × Time Interval	**(24,264)**	**1.955**	**0.006**	**0.151**
Δf_{AB} × Condition × Time Interval	(48,528)	0.715	0.925	0.061

TABLE 3.6: Pairwise comparisons comparing gradual and abrupt change ascending-first cases. (0 ST - ascending-first gradual change conditions. 3, 6 and 12 ST - ascending-first abrupt change conditions.)

(I) Abrupt Fall [ST]	(J) Abrupt Fall [ST]	Mean Difference (I-J)	Std. Error	*p*
0	**12**	**16.5**	**5.0**	**0.007**
	6	**6.6**	**2.7**	**0.035**
	3	5.7	2.9	0.078
12	**0**	**-16.5**	**5.0**	**0.007**
	6	**-9.9**	**3.7**	**0.023**
	3	-10.8	6.6	0.132
6	**0**	**-6.6**	**2.7**	**0.035**
	12	**9.9**	**3.7**	**0.023**
	3	-0.9	4.2	0.834
3	0	-5.7	2.9	0.078
	12	10.8	6.6	0.132
	6	0.9	4.2	0.834

TABLE 3.7: Three-way repeated measures ANOVA comparing gradual and abrupt change descending-first cases.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**20.089**	**<0.001**	**0.646**
Condition	**(3,33)**	**5.866**	**0.003**	**0.348**
Time Interval	**(8,88)**	**16.905**	**<0.001**	**0.606**
Δf_{AB} × Condition	(6,66)	1.320	0.261	0.107
Δf_{AB} × Time Interval	(16,176)	1.050	0.407	0.087
Condition × Time Interval	**(24,264)**	**3.960**	**<0.001**	**0.265**
Δf_{AB} × Condition × Time Interval	(48,528)	1.123	0.271	0.093

TABLE 3.8: Pairwise comparisons comparing gradual and abrupt change descending first cases. (0 ST - descending first gradual change conditions. 3, 6 and 12 ST - descending first abrupt change conditions.)

(I) Abrupt Rise [ST]	(J) Abrupt Rise [ST]	Mean Difference (I-J)[%]	Std. Error	*p*
0	**12**	**17.4**	**6.5**	**0.022**
	6	**10.6**	**3.6**	**0.013**
	3	4.5	2.3	0.074
12	**0**	**-17.4**	**6.5**	**0.022**
	6	-6.8	3.6	0.086
	3	**-12.9**	**5.8**	**0.048**
6	**0**	**-10.6**	**3.6**	**0.013**
	12	6.8	3.6	0.086
	3	-6.1	3.1	0.074
3	0	-4.5	2.3	0.074
	12	**12.9**	**5.8**	**0.048**
	6	6.1	3.1	0.074

frequency elicited similar patterns of build-up. The initial phase (until approximately 10-s) was rapid but later slowed (cf. Anstis and Saida, 1985). The build-up of stream segregation over time is reflected in the highly significant main effect of Time Interval ($p < 0.001$, Table 3.1). Pairwise comparisons within the Time Interval factor showed significant mean differences between the first time-bin and all others ($p < 0.001$, Table 3.4); these differences increased in magnitude with time, from 6.3 percentage points to 47.5 percentage points. When the 19-20 s time-bin was compared with all others it was noted to be significantly different from time intervals 1-13 ($p < 0.05$), but at time intervals exceeding 13 s, the mean differences ceased to be statistically significant ($p > 0.05$), indicating the slowing of build-up. In general, increases in Δf_{AB}, elevated both the rate of build-up and the final extent of segregation.

The main effect of Δf_{AB} was also highly significant ($p < 0.001$, Table 3.1), and pairwise comparisons of the 4 ST case with the 6 ST case (mean difference = 17.1 percentage points, $p < 0.001$) and the 4 ST case with the 8 ST case (mean difference = 31.8 percentage points, $p < 0.001$) were consistent with the observed increase in the extent of segregation at higher frequency separations (Table 3.2). Despite the nominally greater extent of segregation overall for the 500-Hz vs. the 1-kHz case (+7.6 percentage points)—an effect in the opposite direction to that predicted on the basis of frequency resolution in the periphery—this difference was not significant ($p = 0.227$, Table 3.1). However, considering the small differences in ERB spacing between 500 Hz and 1 kHz, it is unsurprising that there was no main effect of overall differences in base frequency.

Gradual-change cases tended to show nominally higher rates of build-up than fixed cases, though this difference was less obvious for the 8 ST case. The ANOVA comparing means of fixed and gradual cases, revealed no significant difference between the two means ($p = 0.360$, Table 3.3). Again, the main effects of Δf_{AB} and Time Interval were highly significant ($p < 0.001$, Table 3.3).

In the case of an abrupt change in base frequency, ascending (abrupt fall) and descending (abrupt rise) cases showed similar patterns of streaming over time. In both cases, the steep rate of build-up was almost identical to that of corresponding gradual-change case up to 10-s. This is as expected, because the stimuli for the gradual and abrupt counterparts are identical up to this point. Shortly after the introduction of an abrupt change in the pattern of gradual drift, a drop in segregation level was visible relative to the corresponding gradual-only reference. This could be observed from the main effect of condition in both the ascending ($p = 0.007$, Table 3.5) and descending ($p = 0.003$, Table 3.7) configurations. As for the previous three-way ANOVAs, the main effects of Δf_{AB} and Time Interval were highly significant ($p < 0.001$ in both cases). The magnitude of the drop in segregation increased with the size of the change; an abrupt 12 ST shift produced the largest drop in segregation level (mean difference = 16.5 percentage points, close to the reported segregation level at the start of the sequence). For the ascending case (abrupt fall), pairwise comparisons using the gradual-change condition as the reference case showed increasing mean differences, and significance, for the 3 ST shift (mean difference = 5.7 percentage points, $p = 0.078$), 6 ST shift (mean difference = 6.6 percentage points, $p = 0.035$), and 12 ST shift (mean difference = 16.5 percentage points, $p = 0.007$); see Table 3.6. Only the 3 ST shift was not significantly different from the gradual case, and even in that instance there was a clear trend in the expected direction. A similar outcome was also observed for the descending (abrupt rise) cases: Gradual vs. 3 ST shift (mean difference = 4.5 percentage points, $p = 0.074$), 6 ST shift (mean difference = 10.6 percentage points, $p = 0.036$), and 12 ST shift (mean difference = 17.4 percentage points, $p = 0.022$); see Table 3.8.

This return to a more integrated percept was maintained over the subsequent 2-3 time-bins, after which segregation increased at a rate comparable to the initial phase of build-up. This pattern accounted for the significant interaction between Condition and Time Interval for the ascending (abrupt fall, $p = 0.006$, Table 3.5) and descending (abrupt rise, $p < 0.001$, Table 3.7) configurations.

3.2.4.2 The effect of rate of change on the extent of segregation

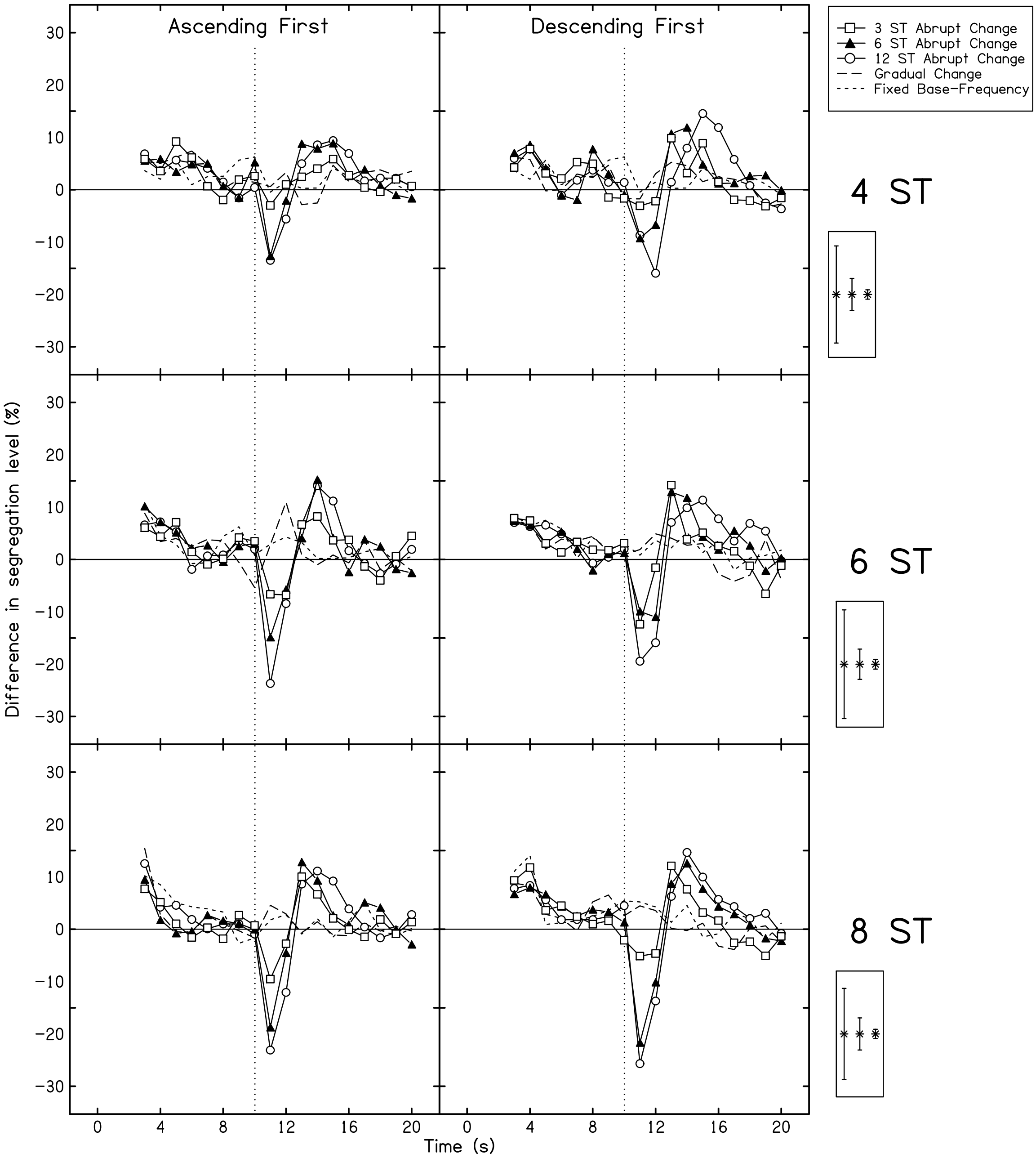

Figure 3.6: Results from Experiment 1 derived from the difference calculations.This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n=n-1, where n=current time-bin) and plotting the value for the the corresponding time-bin (n).The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition for each Δf_{AB} .

To isolate the effect of abrupt changes in base frequency on the subsequent rate of the build-up of streaming from the overall extent of segregation prior to the abrupt change, the difference in segregation level between directly adjacent time intervals was calculated. This facilitates comparison across, e.g., different Δf_{AB} values, for which differences in the extent of segregation immediately prior to the point of the abrupt change can be substantial. To achieve optimum alignment relative to the moment of abrupt change, the raw data were re-analysed such that the abrupt change occurred in the centre of the 9.5-10.5 s time bin (i.e., the first time bin was 0.5-1.5 s, followed by 1.5-2.5, 2.5-3.5, 3.5-4.5 s, etc.). Then, for each time bin, the difference in the extent of segregation between the current and previous time-bins was calculated—i.e., [n-(n-1)], where n=current time-bin. The graphical representation of the difference data are shown in Figure 3.6 for Δf_{AB} = 4, 6, and 8 ST. For the fixed and gradual-change cases, differences in the extent of segregation between adjacent time-bins generally remained within 10 percentage points of the previous interval.

The difference scores for the time bin centred on the transition interval (t=0) and the subsequent interval (t=1) were analysed to identify the effect of the magnitude of a rise/fall in frequency on rate of build-up, and to determine how this was affected by the Δf_{AB} of a sequence. For the abrupt-change conditions, shifts of 3, 6, and 12 ST in base frequency all tended to show a negative mean difference in these scores post-transition, indicating a relative decrease in the extent of segregation. This effect could be observed to persist over the subsequent 2 time-bins. Pairwise comparisons revealed that the 12-ST shift in base frequency consistently resulted in a significant rapid fall in the extent of segregation across all Δf_{AB}s ($p < 0.05$ in all cases, see Table 3.9). The 6-ST shift also caused a significant rapid fall in the extent of segregation, but only at an Δf_{AB}=12 ST ($p = 0.018$). Consistent with this pattern, a three-way repeated measures ANOVA comparing the difference scores showed a significant effect of transition size ($p < 0.001$, see Table 3.10).

As a precaution, given the variability in response time amongst listeners to the abrupt change in base frequency, this analysis was repeated for the averages of t=-1 and t=0 compared with the averages of t=1 and t=2 (see Tables 3.11 and 3.12). The outcomes are broadly consistent with those of the first analysis—although the effect of a 12 ST shift was diminished for Δf_{AB}= 4 ST, it nonetheless approached significance ($p = 0.060$, see Table 3.11). Transition size remained a highly significant factor in the ANOVA when the second epoch was included ($p = 0.004$, see Table 3.12).

Having established that this analysis can provide an effective means of comparing the effects of different types of transition parameters, it can be used to explore the outcomes of some of the other experiments reported here. This approach should prove particularly useful for those experiments involving sequences containing more than one abrupt transition where the extent of segregation immediately prior to transitions other than the first is unlikely to be similar across the conditions that require comparison.

3.2.5 Discussion

The pattern of build-up induced by the fixed base-frequency cases in Experiment 1 was consistent with the known phases of build-up (Bregman, 1978; Anstis and Saida, 1985; Miller and Heise, 1950). Both the initial rapid phase (approximately 10 s) and second slower, more stable phase were clearly evident over the course of the 20-s sequences. Another well-established effect observed was the segregation-promoting influence of larger frequency separations between tone subsets (van Noorden, 1975; Miller and Heise, 1950). For constant, unchanging sequences there appeared to be little or no overall effect of base frequency. This was probably because of the similar levels of overlap in excitation patterns between 'A' and 'B' tones for the lowest and highest base frequencies used, 500 Hz and 1000 Hz (see Figure 3.7).

Despite the gradual cases appearing to elicit a higher rate of build-up than the fixed cases, this difference was not statistically significant. Rather, the effect of gradual change in base frequency on streaming was comparable to that of the fixed cases. This outcome is consistent with the effects of gradual change broadly noted by Rogers and Bregman (1998), and their account of the gradual shifts in stimulus properties as cueing origin from a single source in the environment. This would fail to restart the evidence accumulation process perceptually characterised by build-up (Bregman, 1978), leading to an increase in segregation extent matching that induced by unchanging sequences.

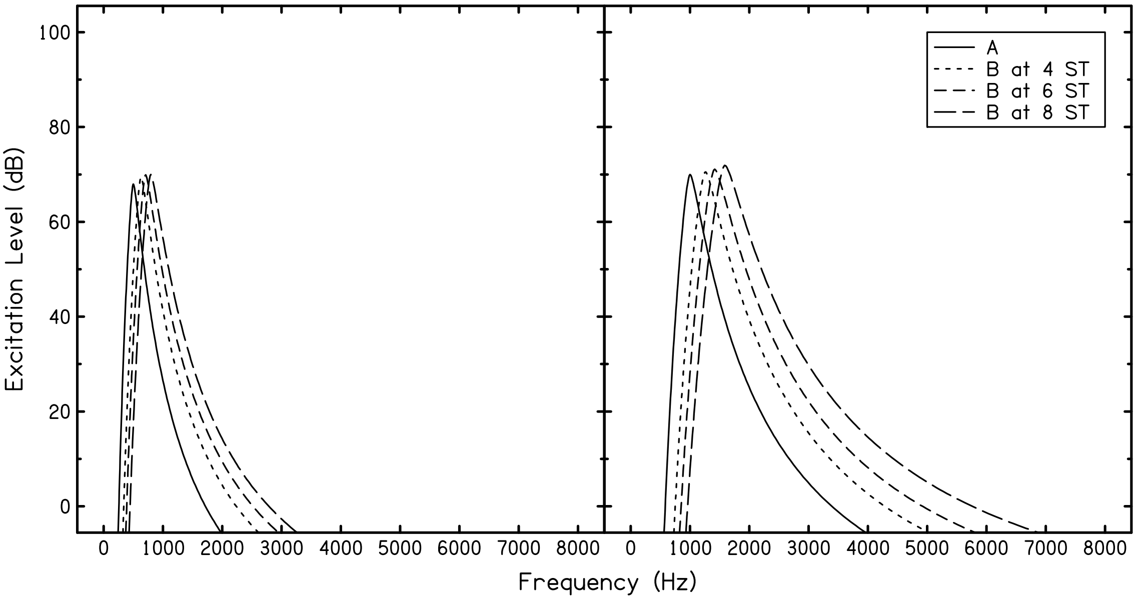

Figure 3.7: The excitation patterns for 'A' and 'B' tones when at minimum and maximum frequency. The left hand panel shows the excitation pattern at the minimum frequency (when A = 500 Hz) and the right hand panel shows the pattern at maximum (A = 1 kHz). In both cases, excitation patterns are largely overlapping, though the degree of overlap decreases for increasing base frequency and frequency separation. A = baseline frequency; B = 4 ST higher; B = 6 ST higher; B = 8 ST higher. Created using the Program for Calculation of Excitation Patterns (Glasberg and Moore, 2005) according to the procedure described in Moore, Glasberg and Baer (1997).

In contrast to the null effect of gradual change, abrupt changes in base frequency resulted in a transient return to a more integrated percept, followed by a rapid rise in segregation which after approximately 4-5 s slows down to a final phase. A resetting effect was observed in response to all changes in base frequency, even for a 3-ST change (although this was not significantly different from the gradual-change case). The 6-ST change produced a greater fall in segregation level and the 12-ST (i.e., one octave) drop resulted in substantial resetting. To establish if the transitions were having a significant effect on streaming, it was necessary to isolate their effect from the continuously occurring build-up of segregation, and to do so the differences in segregation scores between adjacent time intervals were calculated. The ANOVA comparing the extent of segregation across conditions following the transition and the ANOVA comparing these difference scores across conditions both broadly supported the notion of an increasing effect of abrupt change with the size of the transition.

According to the event-accumulation account of build-up, it might be expected that any noticeable abrupt change in acoustic properties would cause a substantial resetting effect, as the correlated abrupt change of both subsets cues common origin. As discussed previously, this was evident in studies by Anstis and Saida (1985), but the experiment reported here clearly demonstrated a more pronounced resetting effect as the magnitude of the frequency shift was increased. The differences between this study and that of Anstis and Saida (1985) could result from the longer TRTs and lower Δf_{AB} used by Anstis and Saida (1985). It is worth noting that a TRT of 125 ms tends to induce a highly integrated percept (see Figure 1.2). It would follow, therefore, that at lower levels of segregation, the scope for an additional fall in segregation (resetting) would be very limited and it might be anticipated that much smaller frequency shifts would be required to completely reset build-up, i.e., of the order of 1 ST. This could also have led to the limited differences between 4 ST and 1 octave in the extent of this resetting/failure to adapt the test sequence. In contrast, the experiment reported here allowed for 10-s of build-up prior to an abrupt change, widening the scope for characterising potential resetting effects. Additionally, Anstis and Saida (1985) required listeners to adjust the stimulus rate. Participant-controlled changes in sequence rate may have interacted with changes in mean frequency, leading to effects such as the observed asymmetry of abrupt shifts up and down in frequency, which was not observed in this study. Whilst the factors outlined above could account for the resetting effect of shifts substantially less than 3 ST observed by Anstis and Saida (cf. the effect of a 3-ST change here, which did not reach significance), it could also be the case that a larger change is required to restart the evidence accumulation process in a gradually changing sequence.

In summary, abrupt changes in base frequency that occur within sequences which vary continually but gradually result in a fall in segregation level. The extent of the drop in segregation increased with the magnitude of the abrupt frequency change but the direction of this change had little effect. Shifts exceeding 3 ST were required to evoke significant resetting and octave shifts resulted in near complete resetting. The differences in outcome for the current experiment and the study by Anstis and Saida (1985) are likely to reflect one or more of the differences in stimulus properties and task design.

3.3 Experiment 2: Gradual and Abrupt Changes in ITD

Using a setup similar to that of Experiment 1, this experiment aimed to determine whether abrupt changes in lateralisation and direction of lateral motion would cause resetting comparable to that of abrupt frequency changes (cf. Rogers and Bregman, 1998). An addition to this setup was the inclusion of conditions involving multiple abrupt alternations in lateralisation. The sequences remained 20 s long but were synthesised at a sampling rate of 40 kHz to allow for greater resolution of stimulus ITDs. ITDs ranged between -0.75 ms/-30 samples (left leading) and +0.75 ms/+30 samples (right leading) to induce a strong sense of lateralisation. The 'A' tone frequency was set at 250 Hz to ensure that all 'A' and 'B' tones remained below 750 Hz even for the largest Δf_{AB} used. This was done to ensure that the ITD cues led to a clear and unambiguous lateralisation.

3.3.1 Method

The general method and procedure for this experiment is described in Chapter 2. This experiment used a continuous assessment method to establish the effects of changes in stimulus properties over the duration of a 20-s 'ABA-'sequence.

3.3.2 Conditions

The conditions listed below are summarised in Figure 3.8. Each condition was presented at a Δf_{AB} of 4, 6, and 8 ST. Group 1 (Left lateralised): Conditions either started left-lateralised or with a left-to-right pattern of drift. Group 2 (Right lateralised): Conditions either started right-lateralised or with a right-to-left pattern of drift.

1. *Constant:* All triplets at centre (i.e., no ITD).
2. *Multiple Abrupt ITD Changes, side-to-centre:* Starting from left (group 1) or right (group 2) to centre every 3 triplets (ITD = ±0.75 ms) and back again.
3. *Multiple Abrupt ITD Changes, side-to-side:* Starting from left (group 1) or right (group 2) to the contralateral side every 3 triplets (ITD = ±0.75 ms).

4. *Gradual ITD drift:* The sequence starts with maximum lateralisation on the left (group 1) or right (group 2) (ITD = ±0.75 ms) and moves gradually to the contralateral side and back again over 50 triplets. The sequence ends one step before maximum lateralisation on the contralateral side.

5. *Single Abrupt Change, side-to-centre:* As for condition 4, but at 10 s (triplet 26), the sequence abruptly returns to the centre and resumes moving towards the contralateral side at the same rate as previously. At 15 s the sequence reaches maximum lateralisation, at which point it changes direction and returns to the centre by 20 s (triplet 50).

6. *Single Abrupt Change, side-to-side:* As for condition 4, but at 10 s (triplet 26), the sequence returns to the left (group 1)/right (group 2) and resumes moving to the contralateral side at the same rate as previously, reaching maximum lateralisation at the contralateral side by 20 s (triplet 50).

The hypotheses for this experiment are broadly comparable with those of the first experiment; although according to peripheral channelling accounts (which argue a stronger effect of stimulus properties that result in changes in excitation pattern) weaker effects might be expected. In the context of the results from Experiment 1 and the earlier findings of Rogers and Bregman (1998), the outcome for the gradual change case would not be expected to differ significantly from the constant cases. It would be expected that abrupt changes could cause resetting, but how this is manifest is likely to differ when there are a rapid series of transitions rather than just one. Specifically, given the limited time for recovery between transitions, it is likely that an overall suppression of build-up might be observed in the rapid alternations case (conditions 2 and 3).

For both rapid alternating and the single abrupt change cases, an increasing extent of resetting might be expected with any changes of larger magnitude. On that basis, a change in lateralisation from one side to the other could be expected to have a much stronger effect than that from side-to-centre, but note that Rogers and Bregman (1998) did not observe such a difference between these cases for a single transition at the inducer-test boundary.

3.3.3 Participants and Procedure

Twelve listeners took part in this experiment. No participants reported any hearing difficulties and pure tone audiometry revealed thresholds within normal limits. As described in Chapter 2, all conditions were presented within each of the 10 blocks, which were split over 2 sessions. Listeners were numbered to allow analysis of any directional three-way repeated measures ANOVA comparing of lateralisation. Odd-numbered listeners were presented conditions 1-5 in blocks using the order Groups 1-2-1-... (left-right-left-) for successive blocks. Even-numbered listeners were presented blocks in the order Groups 2-1-2-... (right-left-right).

3.3.4 Results

3.3.4.1 Effects of Δf_{AB}, Condition and Time Interval

There was no evidence of any systematic or significant differences in outcomes between Group 1 and Group 2 configurations, and so the results were merged into a single dataset for further analysis. The mean patterns of stream segregation across conditions are shown for all three frequency separations in Figure 3.9. Two three-way ANOVAs, in conjunction with pairwise comparisons, were used to analyse these data. The first compared the constant, gradual, and multiple abrupt-change cases (to-centre, to-side) over the 20-s test sequence duration (Figure 3.9, left-hand column); the second compared the gradual, and single abrupt change cases (to-centre, to-side) for the time-intervals subsequent to the transition (11 s onwards) (Figure 3.9, right-hand column). As expected, both ANOVAs showed significant main effects of Δf_{AB} and Time Interval ($p < 0.001$ and $p = 0.003$, see Tables 3.13 and 3.16). In general, there were limited differences between the conditions at 4 ST (Figure 3.9), possibly due to floor effects. For Δf_{AB}= 6 ST and 8 ST, greater differentiation between the conditions could be observed.

Comparison of the constant, gradual, and multiple abrupt-change cases showed a highly significant main effect of condition ($p < 0.001$, see Table 3.13). Pairwise comparisons indicated that these differences were accounted for primarily by the mean reduction in the extent of segregation for the multiple abrupt changes: side-to-side condition when compared with all other cases ($p \leq 0.023$, Table 3.14). There was also

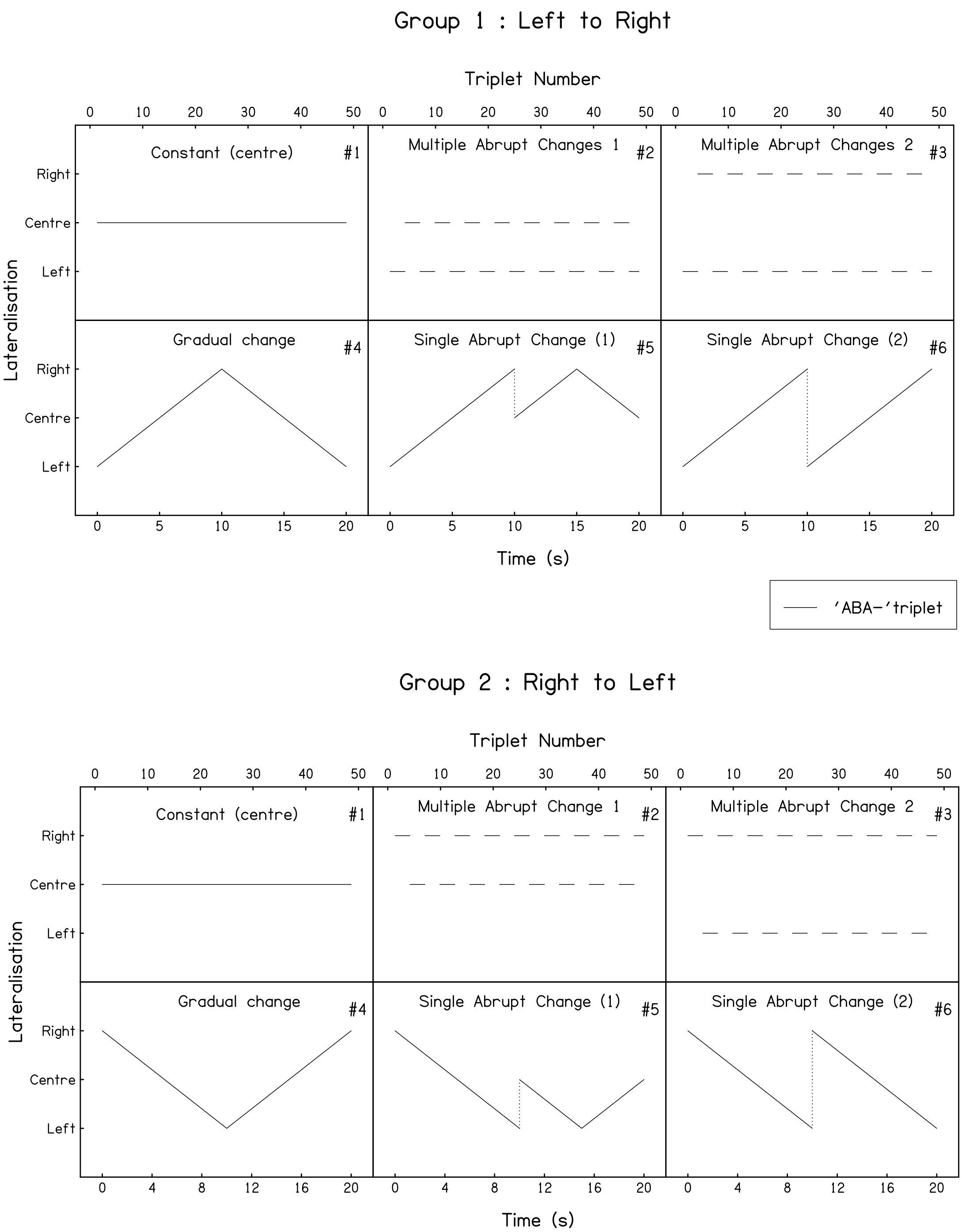

FIGURE 3.8: Illustration of the conditions in Experiment 2. The panels show the trajectory of ITD changes in constant, gradual, alternating and abrupt change conditions over the course of a 20-s test sequence. Group 1 conditions begin left lateralised and Group 2 conditions begin right lateralised.

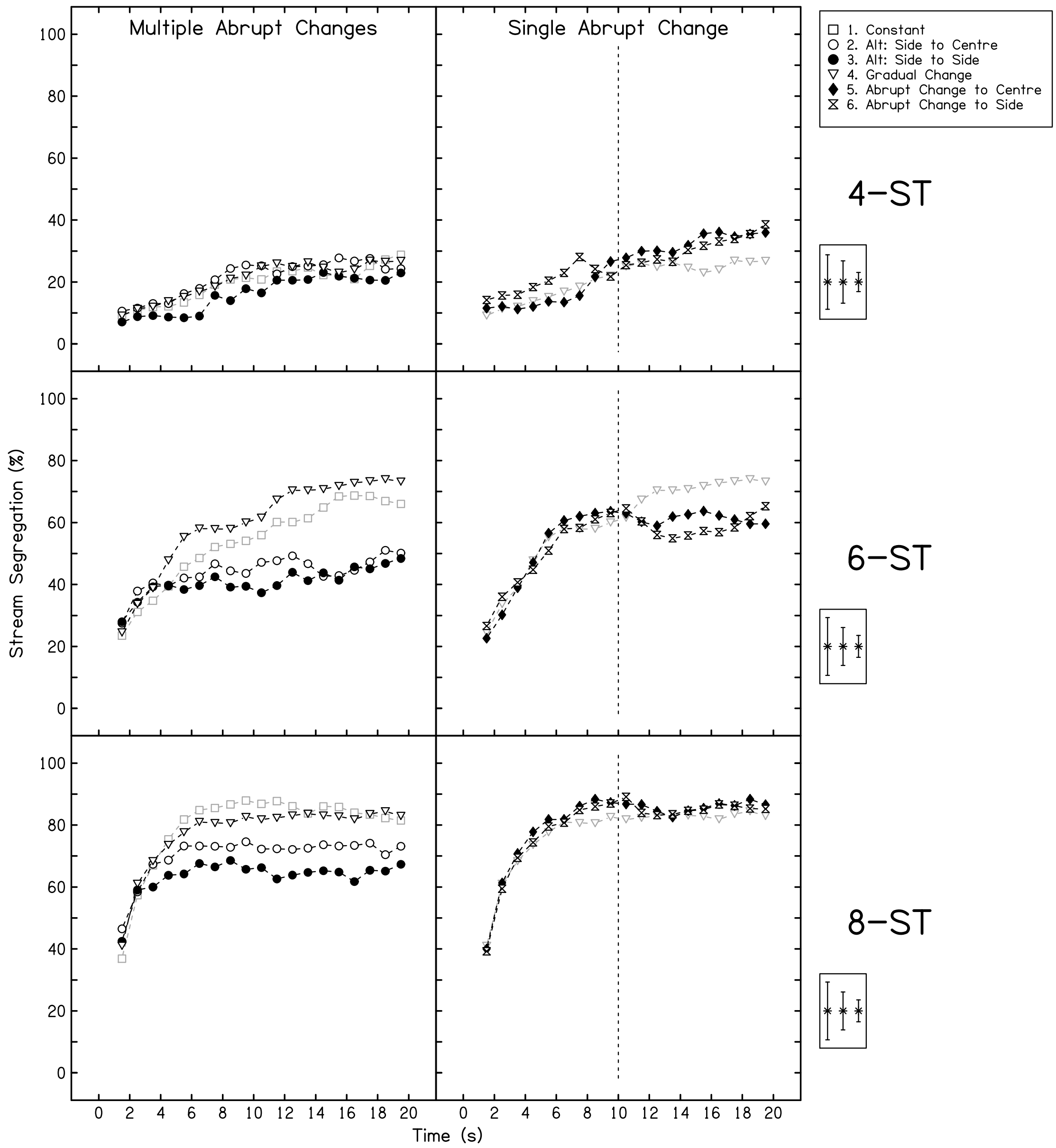

FIGURE 3.9: The stream segregation data averaged across listeners from Experiment 2 displaying the pattern of build-up over the 20-s test sequence for Δf_{AB}s of 4, 6, and 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

evidence of a clear trend in the same direction for the pairwise comparisons between the side-centre alternations vs. the constant or gradual cases, but the magnitude of the effect was smaller than for the side-side cases and did not quite reach significance (p = 0.06 to p = 0.072, Table 3.14). Time Interval also showed a significant main effect ($p < 0.001$, Table 3.13) and interaction with Condition ($p = 0.031$). It is notable that pairwise comparisons between the first time interval and all other intervals were significantly different from each other($p \leq 0.003$ in all cases), whilst the 19-20 s interval was significantly different only from the first 4 time intervals (Table 3.15). This is likely to have arisen from the apparent slower build-up of the multiple abrupt change cases, as the gradual and constant conditions showed a similar pattern of build-up (see Figure 3.9).

Let us now consider the consequences of a single abrupt change in ITD. The pattern of build-up over the first 10-s was almost identical for the gradual and single abrupt-change cases, as would be expected given that the corresponding stimuli for these conditions were identical during this period, so this phase was excluded from the second ANOVA comparing gradual and single abrupt-change cases (Table 3.16). The single abrupt-change cases caused a small drop in segregation level after the transition that was maintained until the end of the sequence, but this failed to reach significance ($p = 0.767$). This could be ascribed to the diminished effects at Δf_{AB}=8 ST, where gradual cases and abrupt-change cases induced comparable segregation levels to those of the constant cases.

3.3.4.2 The effect of rate of change on the extent of segregation

The transient effect of single abrupt changes in this experiment was explored further in terms of differences across conditions in the rate of change of the extent of stream segregation. As for Experiment 1, the raw data were re-analysed to centre the 9.5-10.5 s time bin on the abrupt change time point (i.e., the first time bin was 0.5-1.5 s) and the difference in segregation between neighbouring time bins was computed.

Figure 3.10 shows these data plotted for all frequency separations. For all frequency separations, the difference between adjacent time-bins remained fairly small—usually much less than 10 percentage points—including immediately after the transition. Indeed, only in the 6-ST case is there any evidence of a fall in segregation following

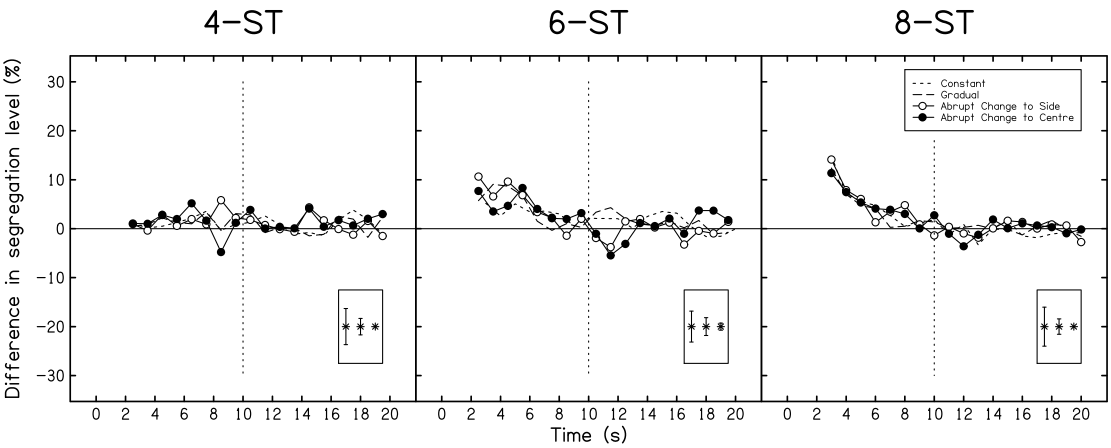

Figure 3.10: Results from Experiment 2 derived from the difference calculations. These values were obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the corresponding time-bin (n). The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition for each Δf_{AB} .

the abrupt change, and that fall is modest ($\approx$ 5 percentage points). The initial phase of all 8-ST cases started at a larger difference in segregation level ($\approx$ 15 percentage points) but that dropped rapidly to around zero, remaining there from 6-s onwards, indicating a fairly rapid initial rate of build-up. The near-absence of an effect of single transitions on the rate of change of segregation level is apparent in the outcomes of the statistical analyses (summarised in Tables 3.17 to 3.20). The first-epoch-only analysis showed no significant effect of single abrupt change at all (see Tables 3.17 and 3.18). Even when the epoch was extended to cover two seconds pre- and post-transition interval, the resetting effect of the abrupt change to the side became notionally significant only for the 6 ST case ($p = 0.02$, mean difference=-8.8 percentage points, Table 3.19). Consistent with this outcome, the interaction term for Δf_{AB} and Lateralisation Condition also became significant ($p = 0.024$, Table 3.20).

3.3.5 Discussion

As for Experiment 1, the effects of frequency separation on overall segregation and the rate of build-up were evident in the constant case and consistent with previous research. In contrast, ITD cues had a relatively limited effect on either the rate of build-up or resetting. Floor effects for the 4-ST cases are perhaps unsurprising in light of the lower base frequency used here (250 Hz), a value selected to ensure that the ITDs applied would provide unambiguous lateralisation cues. As discussed in relation to

Experiment 1, the poorer frequency resolution below 500 Hz (due to broadening of the auditory filters) would have increased the tendency of the percept to remain integrated (Rose and Moore, 1997). This overall reduction in segregation level limited the extent of any resetting or suppression of build-up that might be expected from either multiple or single abrupt change cases when Δf_{AB}= 4 ST. The absence of a resetting effect for the 8-ST cases suggests that frequency separation is a limiting factor on the influence of ITD, though why that is the case is less clear.

Gradual changes in ITD elicited a similar pattern of build-up to the constant cases, consistent with the findings of Rogers and Bregman (1998). This outcome lends weight to their suggestion that gradual changes cue a common source, preserving the ongoing evidence accumulation process.

The greatest effect of ITD cues on stream segregation was observed for the sequences containing multiple abrupt changes. The partial suppression of the build-up in segregation found in the abruptly alternating conditions is probably a result of continuous resetting. If, as previously found, any large abrupt ITD change led to a resetting of the evidence accumulation process required to hear stream segregation (Rogers and Bregman, 1998), then rapidly alternating sequences could be expected to remain more integrated. Alternatively, the changes every 3 triplets might be expected to reflect a common source just as for the gradual change case, maintaining the evidence accumulation process. Neither account reflects the pattern evident here, where alternating the stimulus between left and right lateralisation significantly reduced the segregation level. It could be that the distinct, repeated and correlated changes of 'A' and 'B' tones weighted the percept towards a more integrated state, slowing down the rate of build-up . Single abrupt changes produced a much more limited effect than those shown by Rogers and Bregman (1998) for ITD changes of similar magnitude at the inducer-test boundary. Indeed, with the possible exception of the 6-ST case, there was no apparent effect of a single abrupt change in ITD. The difference between the effect found here and that reported by Rogers and Bregman (1998) might perhaps be a result of the abrupt change occurring here within a sequence that was already moving from one side to the other; in their study, the abrupt change in ITD at the inducer-test boundary was between two constant values.

It is worth noting that the limited influence of ITD cues may be because they are presented alone in this experiment. In 'real-world' listening environments a number of other cues within the auditory stimulus will cue the location of the sound source (such as ILDs arising from the head-related transfer function). The primary reason for selection of ITD in this experiment was to utilise a factor that is used in everyday listening, but which has almost no effect on the pattern of excitation elicited by the stimulus. It is therefore unsurprising that ITD cues alone may not be interpreted in the same way as changes in frequency. It is notable that Rogers and Bregman (1998) obtained the strongest resetting effect in response to location changes generated with the use of a loudspeaker array, which would have provided ITD and ILD cues together. Rogers and Bregman (1998) additionally note that pilot work undertaken in preparation for that study did not reveal a significant effect of abrupt ITD changes when listeners were instructed to rate the extent of segregation and the frequency separation remained constant (as for Rogers and Bregman, 1993), leading the investigators to adopt a procedure where the frequency separation was adjusted in response to the previous trial to make the percept increasingly ambiguous.

3.4 General Discussion

Experiments 1 and 2 clearly demonstrate that the influence of an abrupt change in sequence properties on the build-up of streaming depends upon the particular stimulus property that is being varied. In the case of base frequency, a single abrupt change within a continually varying sequence has a substantial resetting effect, leading to a near-complete loss of build-up for rises or falls of one octave. The extent of resetting is dependent on the magnitude of the abrupt change, but there is no effect of direction. The extent of this resetting for abrupt frequency change strongly contrasts with the effect of large changes in ITD cues which demonstrate an effect which ranges from small (at best) to negligible. The discrepancy between the results of these two experiments would broadly support the suggestion that build-up was mediated by frequency-specific neural populations as suggested by the multi-second neural adaptation model of build-up (either centrally or peripherally). Nonetheless, there is some suggestion that changes in location cued by ITD have some influence on build-up, an aspect which is not accounted for by such a model.

The different degree of influence for changes in ITD and frequency could be due to the lower salience of the abrupt changes in ITD compared to the shifts in base frequency used in Experiment 1. In the case of a stimulus that moves gradually from one side to the other, a sudden shift back to the contralateral side may be considered a less salient change than a sudden rise or fall by an octave within a gradually ascending or descending sequence. Indeed, some researchers have claimed that pitch is an indispensable attribute of auditory objects (Kubovy, 1981; see van Valkenberg and Kubovy, 2003). This may, to some extent, explain the discrepancy in outcome for single abrupt changes in ITD between the current experiment and the studies by Rogers and Bregman (1998) and Roberts et al. (2008), which observed a clear effect of these changes. In those studies, the abrupt changes occurred within otherwise constant sequences, and so may have been a stronger indicator of a new acoustic event.

In accordance with the standard version of the evidence accumulation hypothesis, any abrupt change in frequency of sufficient salience would signal a new sound event, resulting in near-complete resetting of stream segregation. The results of Experiment 1, however, demonstrate that increasing the size of the abrupt change produces a more substantial resetting effect. Whilst these results do not exclude an account of resetting broadly based on the evidence accumulation model, that model would require some modification. For example, the partial resetting following smaller abrupt changes may reflect a temporary bias in evidence-accumulation towards a more integrated percept that is proportional to the size of the change. An alternative (more Gestalt-based) approach would be to consider what information about the source may be obtained by the auditory system from an abrupt change in sequence properties. Correlated shifts of both tone subsets in the same direction and to the same extent may provide strong evidence of origin from a common acoustic source. Such an account could provide an explanation for both resetting and the more integrated percept produced by rapidly alternating ITD sequences.

In summary, Experiments 1 and 2 demonstrate that abrupt changes in a stimulus property can cause varying degrees of resetting depending on the property being altered and the extent to which it is being changed. The resetting effect generally supports many of the accounts of build-up; in accordance with functional accounts of build-up (Bregman, 1978), an abrupt change restarts the process of evidence accumulation. In the case of neural accounts of build-up, the increased tendency for segregation results from habituation of a specific neural population. An abrupt change in stimulus properties therefore results in stimulation of a distinct neural population, thereby restarting the process of build-up (Micheyl et al., 2005; Pressnitzer et al., 2008). However neither account seems adequately to explain the partial resetting caused by smaller changes in frequency or ITD or the suppression of segregation in sequences with multiple abrupt alternations in lateralisation.

TABLE 3.9: Pairwise Comparisons, t=0 vs t=1
(*p*-values shown in black, mean difference scores [%]in grey.)

		Size of frequency change (ST)			
		0	3	6	12
Δf_{AB}	4	0.127	0.865	0.376	**0.010**
		-7.5	-0.6	-7.0	**-14.0**
	6	0.099	0.073	0.171	**0.030**
		-8.7	-7.3	-10.6	**-19.7**
	8	0.178	0.933	**0.018**	**0.007**
		-8.0	-0.6	**-5.8**	**-24.4**

TABLE 3.10: Three-way repeated measures ANOVA
t=0 vs t=1

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	1.603	0.224	0.127
Direction (Rise vs Fall)	(1,11)	0.402	0.539	0.035
Transition Size	**(2,22)**	**11.342**	**<0.001**	**0.508**
Δf_{AB} × Direction	(2,22)	1.914	0.171	0.148
Δf_{AB} × Transition Size	(4,44)	1.437	0.238	0.116
Direction × Transition Size	(2,22)	0.119	0.888	0.011
Δf_{AB} × Direction × Transition Size	(4,44)	1.475	0.232	0.117

TABLE 3.11: Pairwise Comparisons, t=average(t=-1,t=0) vs average(t=1,t=2)
(*p*-values shown in black, mean difference scores in grey.)

		Size of frequency change (ST)			
		0	3	6	12
Δf_{AB}	4	0.456	0.343	0.183	0.060
		-5.7	-5.3	-10.5	-13.0
	6	0.296	0.299	0.112	**0.019**
		-10.4	-6.5	-13.6	**-21.7**
	8	0.178	0.402	**0.012**	**0.015**
		-9.8	-6.0	**-20.6**	**-26.0**

TABLE 3.12: Three-way repeated measures ANOVA
average(t=-1, t=0) vs average(t=1, t=2)

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	1.193	0.322	0.098
Direction (Rise vs Fall)	(1,11)	0.465	0.509	0.041
Transition Size	**(2,22)**	**7.382**	**0.004**	**0.402**
Δf_{AB} ×Direction	(2,22)	1.194	0.322	0.098
Δf_{AB} ×Transition Size	(4,44)	1.152	0.345	0.095
Direction × Transition Size	(2,22)	0.059	0.943	0.005
Δf_{AB} × Direction × Transition Size	(4,44)	2.337	0.070	0.175

Table 3.13: Three-way repeated measures ANOVA comparing constant, gradual and multiple abrupt change ITD cases.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	49.367	<**0.001**	**0.818**
Condition	**(3,33)**	**8.474**	<**0.001**	**0.435**
Time Interval	**(18,198)**	**7.961**	<**0.001**	**0.420**
Δf_{AB} × **Condition**	**(6,66)**	**2.492**	**0.031**	**0.185**
Δf_{AB} × **Time Interval**	**(36,396)**	**1.958**	**0.001**	**0.151**
Condition × Time Interval	**(54,594)**	**3.520**	<**0.001**	**0.242**
Δf_{AB} × **Condition × Time Interval**	**(108,1188)**	**1.655**	<**0.001**	**0.131**

Table 3.14: Pairwise comparisons of constant, gradual and multiple abrupt change ITD conditions.

(I) Condition	(J) Condition	Mean Difference (I-J)[%]	Std. Error	*p*
Constant	Gradual	-1.8	2.1	0.412
	Alt: side-centre	5.8	2.9	0.072
	Alt: side-side	**10.9**	**2.6**	**0.001**
Gradual	Constant	1.8	2.1	0.412
	Alt: side-centre	7.6	3.6	0.060
	Alt: side-side	**12.7**	**3.3**	**0.003**
Alt: side-centre	Constant	-5.8	2.9	0.072
	Gradual	-7.6	3.6	0.060
	Alt: side-side	**5.1**	**1.9**	**0.023**
Alt: side-side	**Constant**	**-10.9**	**2.6**	**0.001**
	Gradual	**12.7**	**3.3**	**0.003**
	Alt: side-centre	**-5.1**	**1.9**	**0.023**

Table 3.15: Pairwise comparisons of time interval (1-2 s vs all other time intervals and 19-20 s vs all other time intervals) derived from analysis of constant, gradual and multiple abrupt change change ITD cases.

(I) Time_Interval	(J) Time_Interval	Mean Difference (I-J) [%]	Std. Error	*p*
1-2	**2-3**	**-9.1**	**1.7**	**<0.001**
	3-4	**-13.0**	**2.4**	**<0.001**
	4-5	**-15.8**	**3.1**	**<0.001**
	5-6	**-18.8**	**3.9**	**0.001**
	6-7	**-20.7**	**4.6**	**0.001**
	7-8	**-22.7**	**5.0**	**0.001**
	8-9	**-23.1**	**5.6**	**0.002**
	9-10	**-24.0**	**5.9**	**0.002**
	10-11	**-24.2**	**6.3**	**0.003**
	11-12	**-25.5**	**6.5**	**0.002**
	12-13	**-26.4**	**6.5**	**0.002**
	13-14	**-26.2**	**6.7**	**0.003**
	14-15	**-26.6**	**6.7**	**0.002**
	15-16	**-26.6**	**6.6**	**0.002**
	16-17	**-26.6**	**6.4**	**0.002**
	17-18	**-27.9**	**6.1**	**0.001**
	18-19	**-27.7**	**6.4**	**0.001**
	19-20	**-28.2**	**6.6**	**0.001**
19-20	**1-2**	**28.2**	**6.6**	**0.001**
	2-3	**19.2**	**6.8**	**0.016**
	3-4	**15.3**	**6.2**	**0.031**
	4-5	**12.5**	**5.5**	**0.045**
	5-6	9.5	4.6	0.064
	6-7	7.5	3.8	0.070
	7-8	5.5	3.7	0.164
	8-9	5.2	3.1	0.120
	9-10	4.2	2.6	0.133
	10-11	4.1	2.3	0.110
	11-12	2.8	2.2	0.228
	12-13	1.9	1.9	0.328
	13-14	2.0	1.7	0.247
	14-15	1.7	1.4	0.269
	15-16	1.6	1.5	0.295
	16-17	1.7	1.0	0.132
	17-18	0.4	0.7	0.608
	18-19	0.5	0.6	0.394

Table 3.16: Three-way repeated measures ANOVA comparing gradual and single abrupt change ITD cases.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**28.563**	**<0.001**	**0.722**
Condition	(2,22)	0.268	0.767	0.024
Time Interval	**(8,88)**	**3.153**	**0.003**	**0.223**
Δf_{AB} × **Condition**	**(4,44)**	**3.158**	**0.023**	**0.223**
Δf_{AB} × Time Interval	(16,176)	0.471	0.958	0.041
Condition × Time Interval	(16,176)	1.092	0.366	0.090
Δf_{AB} × Condition × Time Interval	(32,352)	1.041	0.410	0.086

Table 3.17: Pairwise Comparisons, t=0 vs t=1
(*p*-values shown in black, mean difference scores in grey.)

		Size of lateralisation change		
		No Change	To Centre	To Side
Δf_{AB}	4	0.963	0.204	0.504
		-0.2	*3.1*	*-1.0*
	6	0.827	0.189	0.304
		-0.4	*-3.9*	*1.7*
	8	0.557	0.099	0.130
		2.6	*-4.0*	*-3.8*

Table 3.18: Two-way repeated measures ANOVA,
t=0 vs t=1

Factor/Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	0.274	0.763	0.024
Lateralisation Condition	(2,22)	0.589	0.051	0.051
Δf_{AB} × Lateralisation Condition	(4,44)	2.210	0.167	0.167

Table 3.19: Pairwise Comparisons, t=average(t=-1,0) vs average(t=1,t=2)
(*p*-values shown in black, mean difference scores in grey.)

		Size of lateralisation change		
		No Change	To Centre	To Side
Δf_{AB}	4	0.896	0.077	0.284
		0.9	*-7.7*	*7.0*
	6	0.338	0.089	**0.020**
		3.6	*-4.6*	***-8.8***
	8	0.380	0.973	0.323
		-2.0	*0.1*	*-3.3*

TABLE 3.20: Two-way repeated measures ANOVA,
t=average(t=-1, t=0) vs average(t=1, t=2)

Factor/Factor Interaction	df	F	p	η_p^2
Δf_{AB}	(2,22)	0.320	0.730	0.028
Lateralisation Condition	(2,22)	1.467	0.252	0.118
Δf_{AB} × Lateralisation Condition	**(4,44)**	**3.123**	**0.024**	**0.221**

Chapter 4

Abrupt Changes in Level and Timbre

4.1 Introduction

Following on from the experiments presented in Chapter 3, Experiments 3 and 4 explored the effect of abrupt changes within otherwise constant sequences. The results of Experiments 1 and 2 were broadly consistent with the peripheral channelling account of streaming, although both the functional account of streaming (Bregman, 1978) and neural habituation of frequency-specific population (Micheyl et al., 2005; Pressnitzer et al., 2008) provide plausible alternative explanations for these results. In Experiment 1 it was established that sudden changes in base frequency, which affect the excitation pattern of a sound stimulus, had a significant impact on the dynamics of streaming. In contrast, changes in lateralisation cued by ITD (which left the pattern of excitation unaltered) exerted a much lesser effect on build-up. The abrupt changes in Experiments 1 and 2 were presented within the context of a continually varying sequence. As gradual changes had little influence on the build-up of streaming, the two experiments presented within this chapter investigated abrupt changes in otherwise fixed sequences.

The experimental paradigm was extended to include two abrupt change cases. Despite the limited effect of a single abrupt ITD change presented in Experiment 2, there was clear suppression of build-up in response to rapid alternations in lateralisation.

Therefore the following experiments included one case in which stimulus properties changed rapidly, and others in which abrupt changes occurred less frequently. The first experiment of this chapter, Experiment 3, varied timbre using pure tones and tone dyads; these dyads comprised pairs of closely spaced tones such that changing between a pure tone and a tone dyad had only a negligible effect on the pattern of excitation induced by the sounds. Experiment 4 altered the presentation level of a pure tone sequence, thereby affecting the level and spread of excitation. As in the previous chapter, a continuous assessment procedure permitted investigation of the duration and extent of effects resulting from these abrupt changes.

Whilst studies into the effects of timbre on stream segregation have demonstrated a stronger effect of spectral differences than variation in temporal features (Hartmann and Johnson, 1991; Wessel, 1979; see Chapter 1) they have tended to explore the effect of changes between tone subsets or target and distractor tones (e.g., Cusack and Roberts, 2000, experiment 1). The effects of changes applied to the whole triplet have not been investigated. Additionally, little attention has been paid to the absolute effect of timbre on streaming (i.e., whether some timbres promote higher rates of build-up than others).

One notable exception is the study by Singh and Bregman (1997) which included monotimbral 'ABA-' sequences in the investigation of spectral and temporal features of complex tones. The Δf_{AB} of a test sequence was increased or decreased over time, until the listener recorded that the sequence was perceived as segregated, providing a measure of the TCB. In general, spectral differences between tone subsets were found to result in higher segregation levels than temporal differences, but monotimbral sequences consisting of two harmonics produced similar TCBs to those comprising four harmonics. Those monotimbral sequences with steep rise/slow fall structures tended to remain integrated for longer than gradual rise/sharp fall structures. However, this difference was only significant for cases where Δf_{AB} increased.

These results were at least partly consistent with the findings of Cusack and Roberts (2000, experiment 2) who used an objective, rhythm detection task to explore the effect of timbral contrast between tone subsets. Listeners were required to determine whether an 'ABAB' sequence remained isochronous throughout a trial or became non-isochronous. The 'A' and 'B' subsets were set such that both subsets were pure tones, both were narrow-band noises, or the two subsets were different. An irregularity in rhythm was more easily detected in cases where the percept remained more integrated. There was no significant difference between the monotimbral pure tones and both narrow-band noise conditions. However, in cases where the timbre of 'A' and 'B' subsets differed, performance was significantly worse, indicating that the percept was more segregated.

Both studies (Singh and Bregman, 1997; Cusack and Roberts, 2000) suggest that the timbre of fixed sequences would have little effect on the build-up of streaming. Whilst they demonstrate that differences independent of excitation pattern (e.g., temporal envelope) can enhance streaming when occurring between tone subsets, this provides no insight into the potential effect of correlated changes in timbre applied to both subsets of sounds.

The overall effect of presentation level on stream segregation has previously been explored. It is known that the auditory filter bandwidths broaden with increasing level (Glasberg and Moore, 1990) and, in accordance with peripheral channelling theories, it would be expected that higher stimulus levels would result in a more integrated percept. Rose and Moore (2000) investigated this assertion using a repeating 'ABA-' sequence in which the 'B' tone started at a high frequency and swept towards the lower frequency 'A' tone. Sequences were presented at levels ranging from 40-85 dB SPL. Listeners were required to indicate when they no longer heard the sequence as segregated, thereby providing a measure of the fission boundary. Consistent with the peripheral channelling hypothesis, the Δf_{AB} at the fission boundary tended to increase with higher presentation level. This could be explained by the broadening of auditory filters, leading to a greater extent of overlap of adjacent filters and a more integrated percept. Nonetheless, the effect of overall presentation was relatively modest, such that a difference of 12 dB between sequences might be expected to have little effect on the extent of stream segregation.

There has also been some investigation of the effect of correlated abrupt changes in level (i.e., where both subsets of sounds increase or decrease in level together). Rogers and Bregman (1998) explored the effect of gradual and abrupt changes in overall stimulus level using an inducer-test setup (described in the previous chapter). In addition to the gradual change case, where the inducer level slowly increased from 59 to 71 dBA, two abrupt-change cases were included. In the sudden louder case, the level abruptly rose by 12 dB at the inducer-test boundary (from the inducer level of 59 dBA to the test sequence level of 71 dBA. For the sudden softer case, this was a fall in level from 71 dBA to 59 dBA. The sudden louder (rising level) case induced a significant resetting in the following test sequence, but the sudden softer change (falling level) induced minimal effects that were comparable in magnitude to those of the gradual change case. Using a temporal discrimination task (also described in more detail in Chapter 3), Roberts et al. (2008) observed a slightly weaker asymmetry than Rogers and Bregman (1998), but their results were broadly consistent. Rogers and Bregman (1998) suggest that this asymmetry reflects the greater importance of abrupt increases in level, because such abrupt increases could indicate the onset of new sound sources.

Experiments 3 and 4 were designed to investigate further the effect of abrupt changes in overall timbre and level on stream segregation. The direction of the changes was varied to explore any asymmetry in responses to these transitions, and both rapidly alternating and slower alternating sequences were used. Due to the limited effect of gradual changes and potential limiting effect of continuous change on that of abrupt shifts, the abrupt changes occurred within otherwise steady sequences. The setup of conditions in Experiments 3 and 4 was kept the same to allow comparison of level and timbre effects.

4.2 Experiment 3: Abrupt Changes in Timbre

4.2.1 Method

The method and procedure for this experiment were as described in the General Methods (Chapter 2). Listeners were required to continuously monitor their perception of the 'ABA-' sequence and indicate whether it was either integrated or segregated.

4.2.2 Conditions and Hypotheses

The timbre change in sequences was generated using pure tones and tone dyads (tone pairs). The same pattern of excitation for both was maintained by centring the tone dyads on the same frequency as the corresponding pure tone with a 50 Hz (i.e., ±25

Hz) separation. The 'A' tone (base/centre frequency) was set at 1 kHz and the 'B' tone was higher, varying according to Δf_{AB} (4, 6 or 8 ST). Hence, the components of the tone dyads would always be unresolved and the excitation pattern of a tone dyad and its pure-tone counterpart would be almost identical. Nonetheless, the tone dyads had a distinctly 'rougher' timbre than their pure-tone counterparts, owing to the 50-Hz modulation arising from their interaction within the same auditory filter. The dyads are somewhat reminiscent of the sounds produced by the stridulations of a cricket. To ensure equal level stimuli across conditions, each tone in the dyad was 3dB lower than the corresponding pure tone.

In addition to the constant conditions (i.e., all pure or all dyad) used to establish if there was an absolute effect of timbre on streaming, two types of abrupt-change conditions were created. The first was a rapidly alternating case, where the sequences switched between tone dyad and pure tone every three triplets. This enabled exploration of whether rapid changes would act to suppress build-up, continually resetting this process, or have no effect on streaming. The second, slower, alternating case did the same but only every 13 triplets; this case was presented in two configurations: pure tone at the start and tone dyad at the start. The purpose of these changes every 5.2 s was to provide adequate scope for build-up between transitions so that the full extent of any resetting arising from a particular transition would be evident.

According to the peripheral channelling account of streaming, little effect of any abrupt change would be expected without an associated change in excitation patterns. Similarly, fixed sequences of different timbre would show identical patterns of build-up, as there would be no difference in the pattern of excitation elicited by either pure tone or tone dyad. However, if the perceptual salience of the change determined the degree of any resetting—despite the absence of peripheral channelling cues—the distinct timbre changes would cause substantial resetting in the slowly alternating case and repeated resetting in the rapidly alternating condition would appear as suppression of build-up.

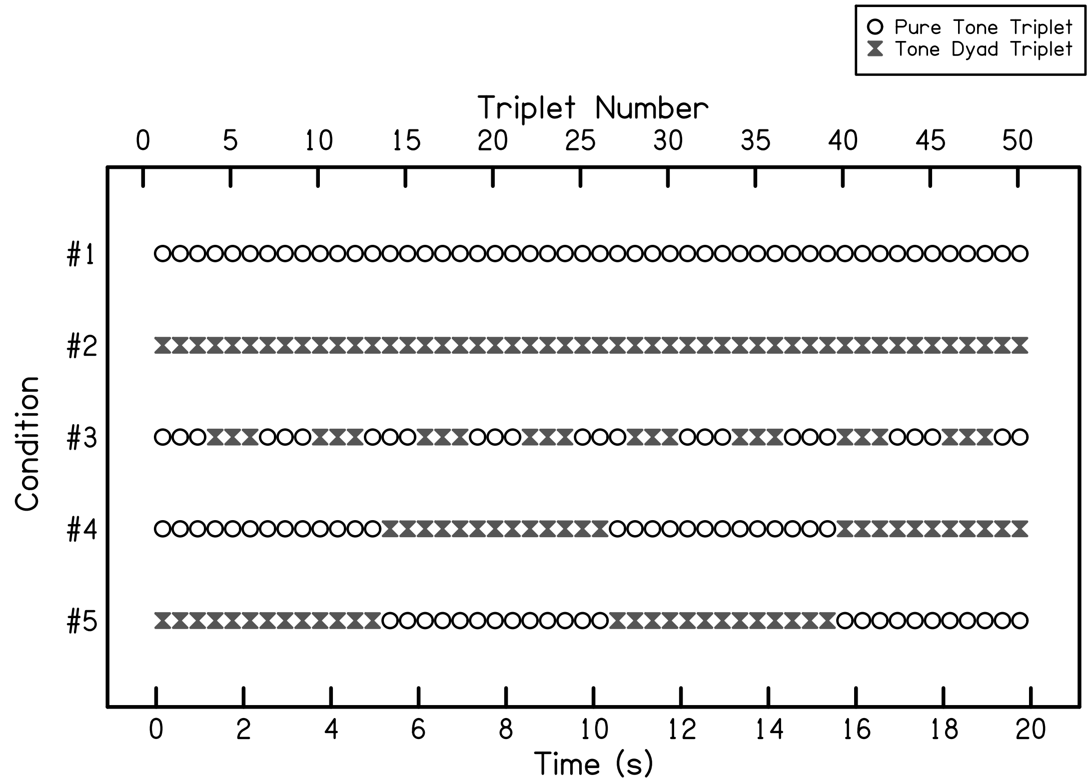

Figure 4.1: Illustration of the conditions in Experiment 3.

The conditions below are summarised in Figure 4.1

1. *Pure Tone:* Sequence composed solely of pure tones with base frequency of 1 kHz.
2. *Tone Dyad:* Sequence composed solely of dyads centred on the corresponding pure tone frequency, with a within-pair separation of 50 Hz.
3. *Rapidly Alternating (3 triplet):* Every 3 triplets (1.2 s) the sequence switches between pure tones and tone dyads, with *pure tones* at the start. The last group consists of only 2 pure-tone triplets.
4. *Slowly Alternating: Pure Tone to Dyad (13 triplet):* Every 13 triplets (5.2 s) the sequence switches between pure tones and dyads & vice versa, with *pure tones* at the start. The last group of tone dyads consists of 11 triplets.
5. *Slowly Alternating: Dyad to Pure Tone (13 triplet):* Every 13 triplets (5.2 s) the sequence switches between pure tones and dyads & vice versa, with *tone dyads* at the start. The last group of pure tones consists of 11 triplets.

TABLE 4.1: Three-way repeated measures ANOVA comparing constant only conditions i.e. Pure Tone Only vs. Tone Dyad Only cases

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**12.631**	**<0.001**	**0.535**
Condition	(1,11)	1.616	0.230	0.128
Time Interval	**(19,198)**	**23.832**	**<0.001**	**0.684**
Δf_{AB} × Condition	(2,22)	2.687	0.090	0.196
Δf_{AB} × **Time Interval**	**(36,396)**	**2.020**	**0.001**	**0.155**
Condition × Time Interval	**(18,198)**	**5.027**	**<0.001**	**0.314**
Δf_{AB} × Condition × Time Interval	(36,396)	1.012	0.454	0.084

4.2.3 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As described in Chapter 2, all conditions were presented during each of the 10 blocks during a single session.

4.2.4 Results

4.2.4.1 Effects of Δf_{AB}, Condition and Time Interval

The results of Experiment 3 were first analysed using three, three-way repeated measures ANOVAs and associated pairwise comparisons. The first ANOVA, summarised in Table 4.1, was specifically to compare the two constant cases (top, left-hand panel of Figures 4.2-4.4). The second ANOVA, summarised in Table 4.2, compared the constant and rapid alternating (3 triplet) conditions (top, right-hand panel of Figures 4.2-4.4), and the third (Table 4.3) compared the constant and slowly alternating (13 triplet) conditions (bottom panels of Figures 4.2-4.4). All three ANOVAs showed significant main effects of Δf_{AB} and Time Interval ($p < 0.001$, in all cases), but there was no main effect of Condition. There were significant interactions between Δf_{AB} and Time Interval ($p = 0.016$ to $p < 0.001$) and between Condition and Time interval ($p < 0.001$, in all cases). The outcomes of these ANOVAs are considered in turn.

First, from the start, dyad-only sequences elicited a more segregated percept than pure-tone-only cases across all frequency separations, with a slower rate of build-up (Figure 4.2), as reflected by the significant interaction terms between Condition and Time interval ($p < 0.001$, Table 4.1. The results for pure tone and dyad sequences

TABLE 4.2: Three-way repeated measures ANOVA comparing constant and rapidly alternating conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**11.475**	**<0.001**	**0.510**
Condition	(2,22)	2.321	0.122	0.174
Time Interval	**(18,198)**	**13.176**	**<0.001**	**0.545**
Δf_{AB} × **Condition**	**(4,44)**	**4.607**	**0.003**	**0.295**
Δf_{AB} × **Time Interval**	**(36,396)**	**1.985**	**0.001**	**0.153**
Condition × Time Interval	**(36,396)**	**4.287**	**<0.001**	**0.280**
Δf_{AB} × Condition × Time Interval	(72,792)	1.055	0.361	0.087

TABLE 4.3: Three-way repeated measures ANOVAcomparing constant and slowly alternating conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**13.179**	**<0.001**	**0.545**
Condition	(3,33)	1.835	0.160	0.143
Time Interval	**(18,198)**	**15.592**	**<0.001**	**0.586**
Δf_{AB} × Condition	(6,66)	2.240	0.050	0.169
Δf_{AB} × **Time Interval**	**(36,396)**	**1.615**	**0.016**	**0.128**
Condition × Time Interval	**(54,594)**	**7.376**	**<0.001**	**0.401**
Δf_{AB} × **Condition × Time Interval**	**(108,1188)**	**1.619**	**<0.001**	**0.128**

showed some tendency to converge towards the end of the 20-s sequence, particularly for larger values of Δf_{AB}. This may have contributed towards the lack of a significant main effect of Condition ($p = 0.230$, Table 4.1).

Second, the rapidly alternating (3 triplet group) condition induced a 'sawtooth-like' pattern of fluctuations in the extent of stream segregation over time (upper right panels of Figures 4.2-4.4). Beyond the first few seconds, the mean value of these rapid alternations showed a clear suppression of overall segregation, again more pronounced at 6 and 8 ST, as reflected by the significant interaction between Δf_{AB} and Condition ($p = 0.003$, Table 4.2).

Third, both of the slowly alternating (13 triplet group) conditions (4 and 5) showed dramatic fluctuations in segregation between highly integrated and highly segregated, corresponding to the alternations between pure tones and tone dyads in the sequence (lower panels of Figures 4.2-4.4). Before the first abrupt transition, the pattern of build-up followed that elicited by the start of either the pure-tone-only (for condition 4) or dyad-only conditions (for condition 5). Following a transition from tone dyads to pure tones, there was an almost complete resetting of build-up. A shift from pure tones to tone dyads resulted in an 'overshoot' of segregation, exceeding that induced by the dyad-only condition at the same point in time. Whilst there was no main effect of Condition (p = 0.160, Table 4.3), the effect of the abrupt changes in triplet timbre was reflected in the significant interaction between Condition and Time Interval ($p < 0.001$, Table 4.3). The use of temporally aligned transitions with opposite polarity in Conditions 4 and 5 led to changes in stream segregation in opposite directions following those transitions; this is reflected in the significant three-way interaction ($p < 0.001$, Table 4.3).

4.2.4.2 The effect of abrupt transitions on the rate of change of the extent of segregation

The transient effects of single abrupt changes in the two slowly alternating (13 triplet) cases were explored further in terms of differences across conditions in the rate of change of the extent of stream segregation. In accordance with the methods described in Chapter 3, the raw data were re-analysed.

Each condition was re-analysed three times in order to centre the time bins appropriately for each of the abrupt changes occurring every 5.2 s. For the first transition at 5.2-s, the initial time-bin was set to 0.7-1.7 s, such that the time bin 4.7-5.7 s was centred on 5.2-s. For the second transition at 10.4-s, the initial time bin was set to 0.9-1.9 s, and for the third transition at 15.6-s, it was set to 0.1-1.1 s. This enabled grouping together of all three tone-to-dyad transitions (the first and third transitions from condition 4 with the second transition from condition 5), and all three dyad-to-tone transitions (the second from condition 4 with the first and third from condition 5) so that any influence of transition number could also be explored for each direction. Figure 4.5 shows these data plotted over the duration of the 20-s sequence for each Δf_{AB} (top, middle, and bottom panels = 4, 6, and 8 ST cases, respectively). As previously, these data were then analysed twice: the first three-way repeated measures ANOVA was run on 1-s intervals pre- and post-transition (see Tables 4.4 and 4.5), and the second was extended to include 2 s pre- and post-transition (Tables 4.6 and 4.7).

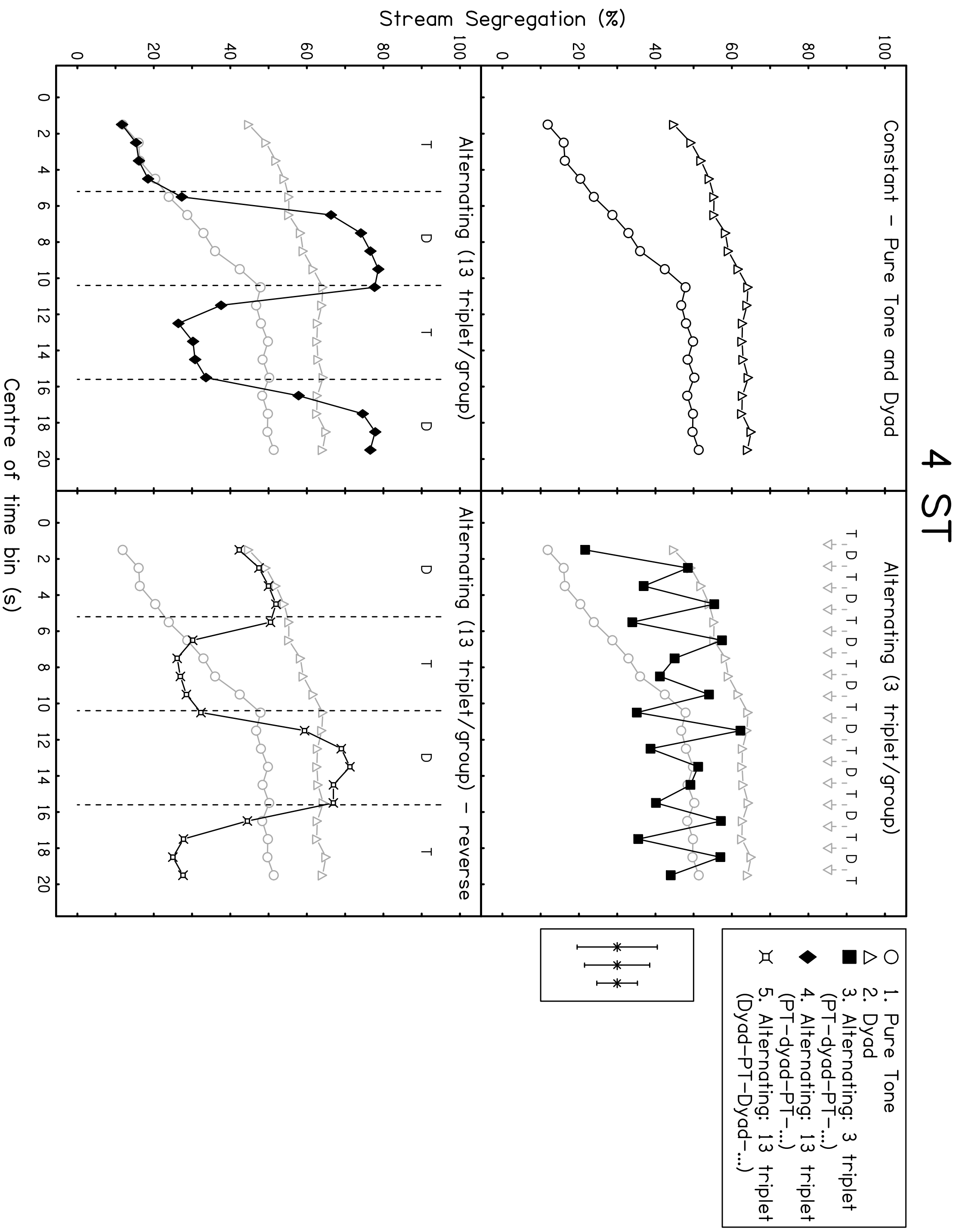

Figure 4.2: The stream segregation data averaged across listeners from Experiment 3 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across conditions.

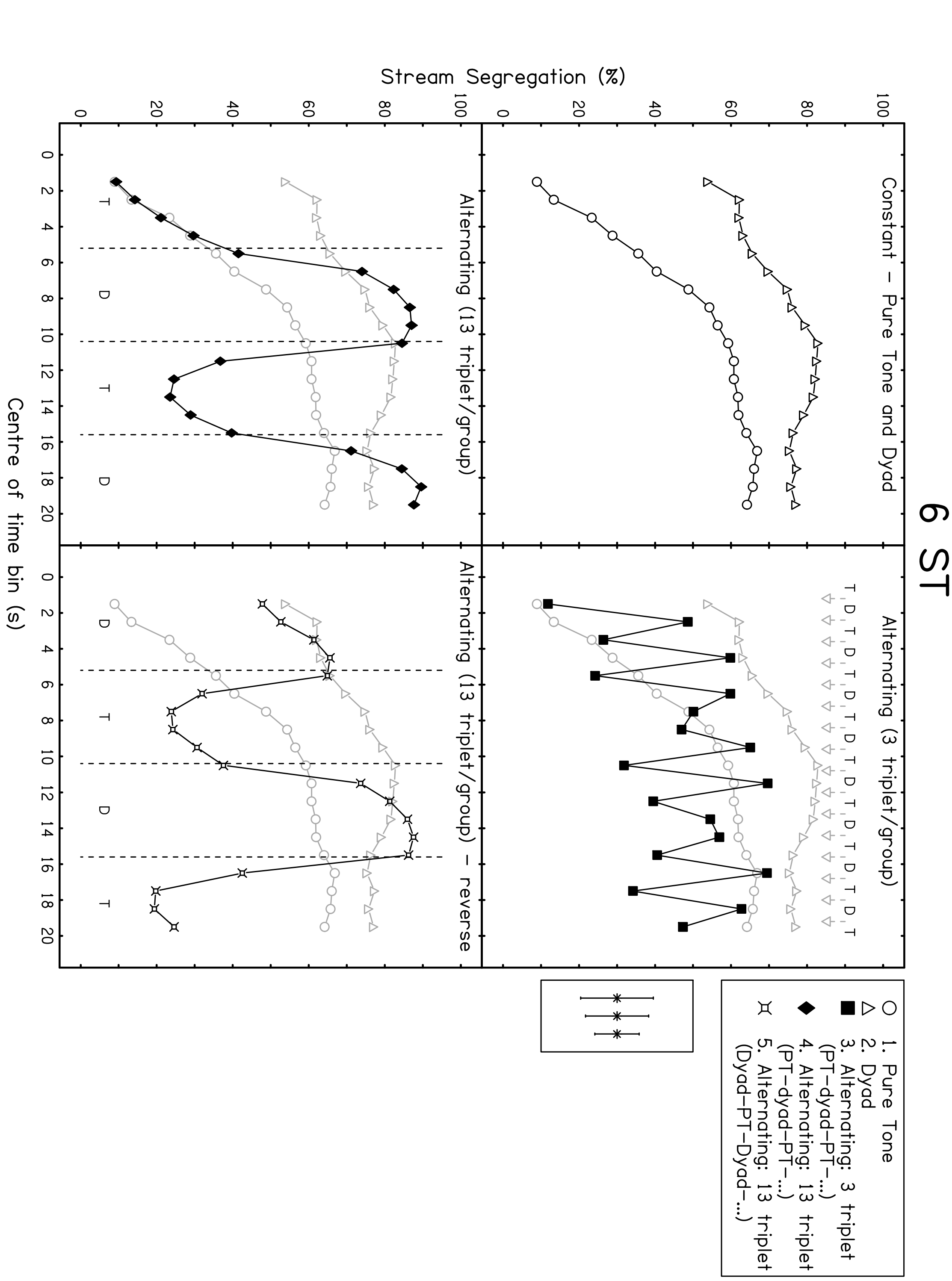

FIGURE 4.3: The stream segregation data averaged across listeners from Experiment 3 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across conditions.

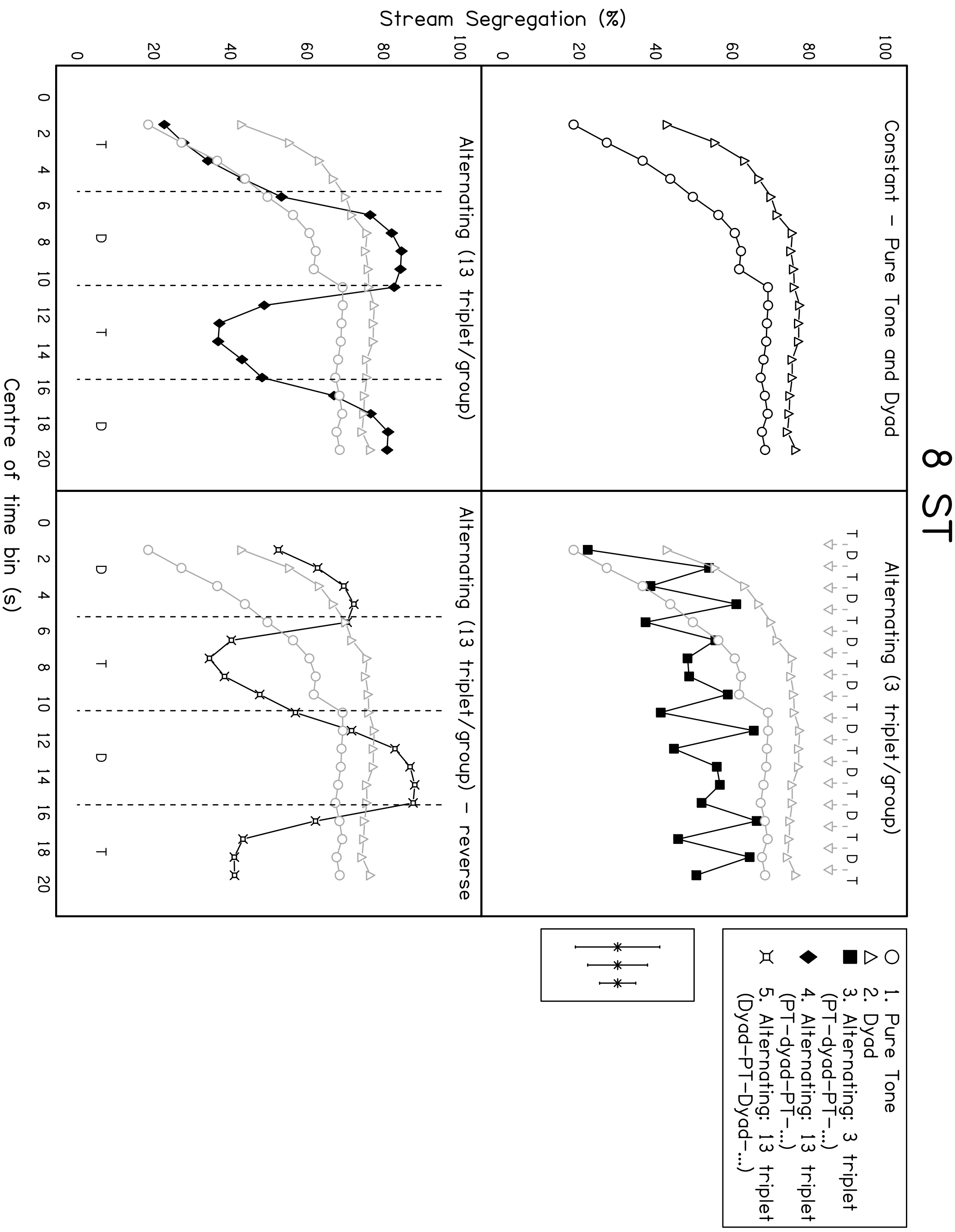

Figure 4.4: The stream segregation data averaged across listeners from Experiment 3 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across conditions.

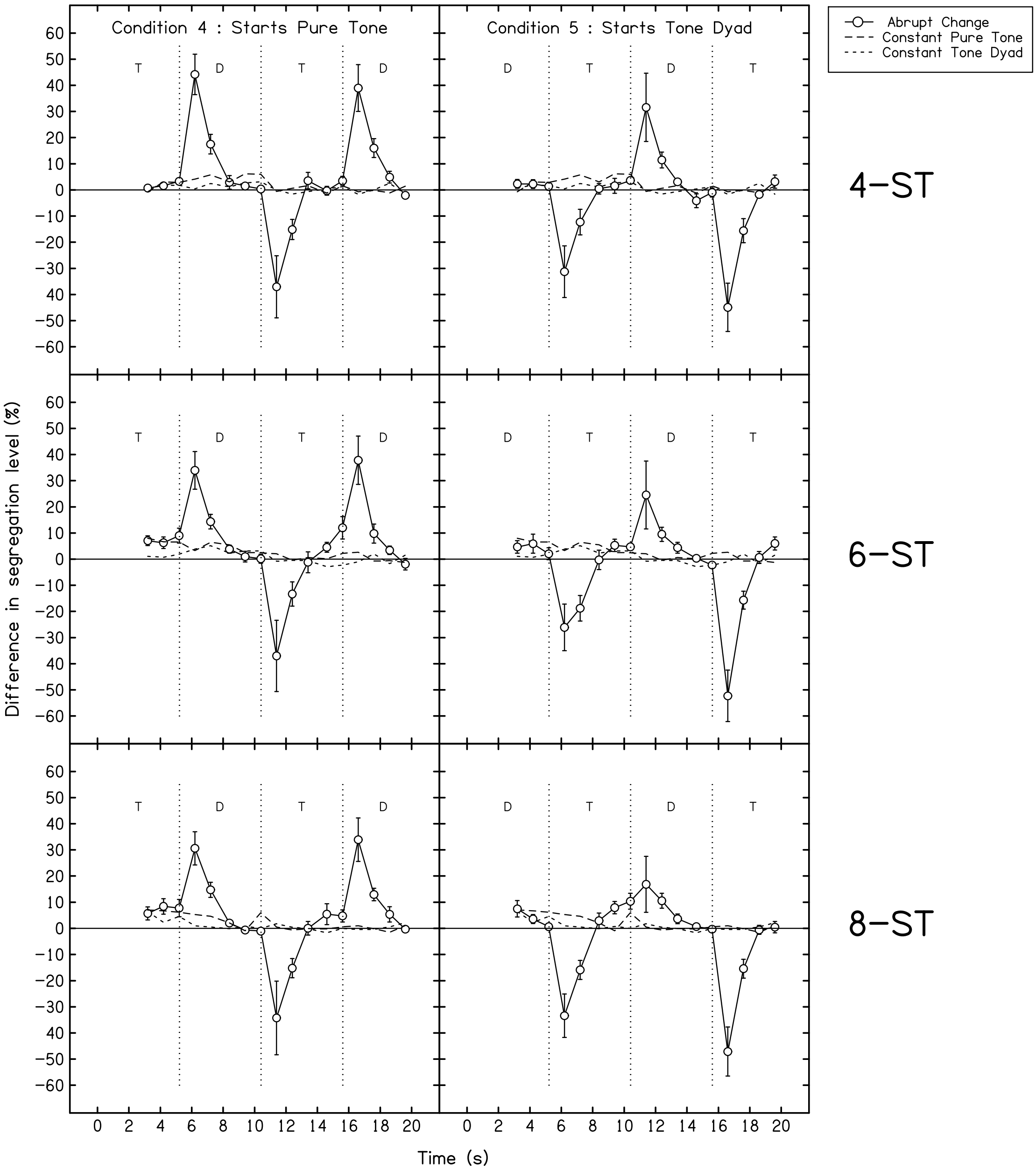

FIGURE 4.5: Results from Experiment 3 derived from the difference calculations. This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n=n-1, where n=current time-bin) and plotting the value for the the corresponding time-bin (n).

TABLE 4.4: Three-way repeated measures ANOVA,
t=0 vs t=1

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**5.408**	**0.012**	**0.330**
Direction (Tone-to-Dyad vs. Dyad-to-Tone)	**(1,11)**	**22.417**	**0.001**	**0.671**
Transition Number	**(2,22)**	**4.967**	**0.017**	**0.311**
Δf_{AB} × **Direction**	**(2,22)**	**9.836**	**0.001**	**0.472**
Δf_{AB} × Transition Number	(4,44)	0.900	0.472	0.076
Direction × Transition Number	**(2,22)**	**18.405**	**<0.001**	**0.626**
Δf_{AB} × **Direction × Transition Number**	**(4,44)**	**19.760**	**<0.001**	**0.642**

TABLE 4.5: Pairwise Comparisons, t=0 vs t=1
(*p*-values shown in black, mean difference scores in grey.)

		Direction of Timbre Change	
		Tone to Dyad	Dyad to Tone
Δf_{AB}	4 ST	**0.009** *13.3*	**0.006** *-14.4*
	6 ST	**0.011** *28.6*	**0.001** *-42.5*
	8 ST	**0.010** *23.9*	**0.001** *-42.7*

TABLE 4.6: Three-way repeated measures ANOVA,
average(t=-1, t=0) vs average(t=1, t=2)

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**9.614**	**0.001**	**0.466**
Direction (Tone-to-Dyad vs. Dyad-to-Tone)	**(1,11)**	**29.165**	**<0.001**	**0.726**
Transition Number	(2,22)	0.682	0.516	0.058
Δf_{AB} × **Direction**	**(2,22)**	**12.924**	**<0.001**	**0.540**
Δf_{AB} × Transition Number	(4,44)	0.556	0.695	0.048
Direction × Transition Number	**(2,22)**	**20.696**	**<0.001**	**0.656**
Δf_{AB} × **Direction × Transition Number**	**(4,44)**	**26.077**	**<0.001**	**0.703**

TABLE 4.7: Pairwise Comparisons, average(t=-1, t=0) vs average(t=1, t=2)
(*p*-values shown in black, mean difference scores in grey.)

		Direction of Timbre Change	
		Tone to Dyad	Dyad to Tone
Δf_{AB}	4 ST	**0.016** *16.6*	**0.003** *-17.4*
	6 ST	**0.011** *32.3*	**<0.001** *-53.9*
	8 ST	**0.018** *25.9*	**<0.001** *-53.6*

In these plots (Figure 4.5) the full extent of the resetting and 'overshoot' described earlier can be observed. Across all frequency separations, the dyad-to-tone transition resulted in a substantial negative peak within 1 s of the change. At the time of the abrupt change the difference in segregation level tended to remain within 0 to 5 percentage points, indicating that limited build-up was occurring at that point. In the following 1-s interval, the difference in segregation level fell significantly for all Δf_{AB} ($p = 0.006$ to $p = 0.001$, Table 4.5). This demonstrated a pronounced resetting effect, which tended to increase with higher Δf_{AB} (mean difference scores accordingly became more negative; from -14.4 percentage points for 4 ST to -42.7 percentage points for 8 ST, see Table 4.5). This resetting continued over the following 2 s but the negative difference in segregation level between adjacent time-bins grew smaller, reflected by the 'recovery' phase of the function, which reaches 0 approximately 3-4 s post-transition. The pairwise comparisons from the second epoch show the effect of the continued resetting, with increasing difference scores of -17.4 to -53.9 percentage points (Table 4.7).

The reverse effect was produced by tone-to-dyad transitions. Here, a rapid rise in segregation level resulted from the tone-to-dyad transition, peaking at approximately 1 s post-transition but continuing over the subsequent 2-3 s. This rapid acceleration and slowing in build-up was shown by the distinct positive peaks in Figure 4.5. This effect was significant in both first and second epoch analyses ($p < 0.02$, in all cases, Tables 4.5 and 4.7). In the first interval analysis, pairwise comparisons showed a more positive difference score for 6-ST (28.6 percentage points) in comparison with 4-ST (13.3 percentage points), but this fell slightly for 8-ST (23.9 percentage points), most likely due to the limited scope for build-up resulting from a higher initial segregation level.

The outcome of the three-way ANOVAs of these transition effects (Tables 4.4 and 4.6) were broadly consistent across the 1-s and 2-s interval versions. The positive difference scores following a tone-to-dyad change in comparison with negative scores subsequent to a dyad-to-tone change, resulted in a significant main effect of direction in both first and second epoch ANOVAs ($p \leq 0.001$, Tables 4.4 and 4.6). Both versions also showed a significant main effect of Δf_{AB} ($p \leq 0.012$), and the following significant interactions: Δf_{AB} × Direction ($p \leq 0.001$), Direction × Transition Number ($p < 0.001$), and the three-way interaction ($p < 0.001$). The interaction between Δf_{AB} and Direction is probably a result of the smaller 'overshoot' peaks at 8 ST, a consequence of the limited scope available for a substantial increase in segregation with higher initial segregation levels. The significant interaction between Direction and Transition Number can be attributed to the limited scope for substantial resetting following a dyad-to-tone transition early on in the sequence, where segregation levels remain low. The finding of a significant main effect of Transition Number (1-s interval analysis only) may arise from the same effect.

4.2.5 Discussion

The results for the constant pure-tone-only cases in Experiment 3 were consistent with those of the previous chapter, and the known effects of frequency separation and time on segregation level (Bregman, 1978; Anstis and Saida, 1985; Miller and Heise, 1950). In comparison, the constant dyad-only case induced a greater initial extent of segregation and a slower rate of build-up. This significant difference in the effect of varying absolute timbre on the extent of segregation and pattern of build-up, contradicts earlier findings (Singh and Bregman, 1997; Cusack and Roberts, 2000). These authors observed limited differences in the degree of segregation evoked by contrasting monotimbral sequences in circumstances where the timbral difference was associated with negligible or absent peripheral channelling cues. It seems unlikely that the differences in timbre between pure tone and tone dyad sequences were substantially greater than the timbre difference created by adjusting the attack and decay times of complex tones (Singh and Bregman, 1997) or the contrast between pure tones and narrowband noises (Cusack and Roberts, 2000). According to a simple peripheral channelling account of build-up, no discernible difference between pure-tone and tone-dyad cases would have been anticipated, as the pattern of excitation on the basilar membrane is broadly the same for both cases. One speculative account for this difference could be the alteration in the timing of neural firing for the two stimuli. Whilst the pattern of excitation remained essentially unchanged for pure tones and their tone-dyad counterparts the dyads are characterised by a regular 50-Hz modulation envelope. Within the frequency-range of the stimuli used in this experiment (975-1612 Hz) the phase-locking of neurons would provide temporal information about the stimuli, including the modulation envelope of the dyads (Rose et al., 1968).

The rapid abrupt changes in timbre generated by the rapidly alternating (3 triplet) case produced a pattern of segregation that differed from that observed for the corresponding case in Experiment 2, in which rapid abrupt changes in lateralisation were generated using ITD cues. In Experiment 2, the result was a suppression in the overall extent of segregation, whereas here that effect was accompanied by an on-going saw-tooth pattern in the extent of segregation as the triplet timbre changed back and forth. During the pure tone portion of the sequence, this reflected the more integrated initial percept of the pure tone only sequence. During the tone dyad portion, this changed to the more segregated initial percept of the tone dyad sequence. The alternations remained relatively regular throughout the course of the sequence, with much less tendency for build-up to occur over time. This again was supported by the results of the ANOVA, the highly significant interaction between frequency and condition reflecting the similar extent of segregation elicited by the alternating (13 triplet) case for all frequency separations. These data would suggest that, when a great enough contrast in timbre is generated, a rapidly alternating sequence is considered more as two separate sequences originating from different sound sources. The short intervals between timbre changes provided limited scope for any build-up, and accordingly, any resetting to occur.

Abrupt changes in the slowly alternating (13 triplet) case produced even more pronounced changes in the pattern of streaming. An abrupt shift from a smoother-to-rougher timbre (pure tone to tone dyad) caused a rapid rise in segregation that exceeded that of the dyad-only case at the corresponding time interval. In contrast, a rougher-to-smoother change in timbre (tone dyad to pure tone) generated a significant and almost-complete resetting, comparable to the initial highly-integrated pure tone percept. This directional pattern was evident across all frequency separations of 'A' and 'B' tone subsets, and can be seen in the outcomes of both types of analysis (i.e., the ANOVA comparing the extent of segregation between constant and slowly alternating cases, and the two ANOVAs examining the difference scores for both transitions).

Again, these patterns of segregation in response to abrupt changes would not have been expected from a purely peripheral channelling account of build-up—the overshoot and resetting may be due to the strong perceptual contrast between the timbre of pure tones and tone dyads. Alternatively, these effects may be a consequence of adaptation by neural populations sensitive to the temporal regularity of the stimulus. To explore this further, Experiment 4 applied analogous changes in level (rather than in timbre) at the transition points in a sequence.

4.3 Experiment 4: Abrupt Changes in Level

Experiment 4 explored the effect of abrupt changes, in this case changes in presentation level. Level was calculated relative to a baseline of 67 dB SPL. Low level sounds were set to 6 dB below the baseline (half the amplitude) and high level sounds were set to 6 dB above (twice the amplitude). As for the previous experiment, the ‘A’ tone was set at 1 kHz and ‘B’ tone adjusted according to Δf_{AB}. The output therefore ranged between 61 - 73 dB SPL.

4.3.1 Method

As for Experiment 3, the method and procedure used continuous assessment of 20-s ‘ABA-’ sequences. The conditions below were presented at Δf_{AB} values of 4, 6, and 8 ST and are summarised in Figure 4.6.

4.3.2 Conditions

1. *Constant Amplitude - max:* All triplets are 6 dB above baseline (‘high’).

2. *Constant Amplitude - min:* All triplets are 6 dB below baseline (‘low’).

3. *Rapidly Alternating (3 triplet):* Rising or falling in level every 3 triplets (1.2 s). The first group (triplets 1-3) are high level. The last group (triplets 49-50, low level) is cut short by 1 triplet (to achieve duration = 20 s).

4. *Slowly Alternating (13 triplet):* Rising or falling in level every 3 triplets (1.2 s). The first group (triplets 1-3) are low level. The last group (triplets 40-50, high level) is cut short by 2 triplets.

5. *Slowly Alternating Reversed (13 triplet):* As Condition 4, but alternation order is reversed, such that the first group (triplets 1-13) are high level whilst the last (triplets 40-50) are low level.

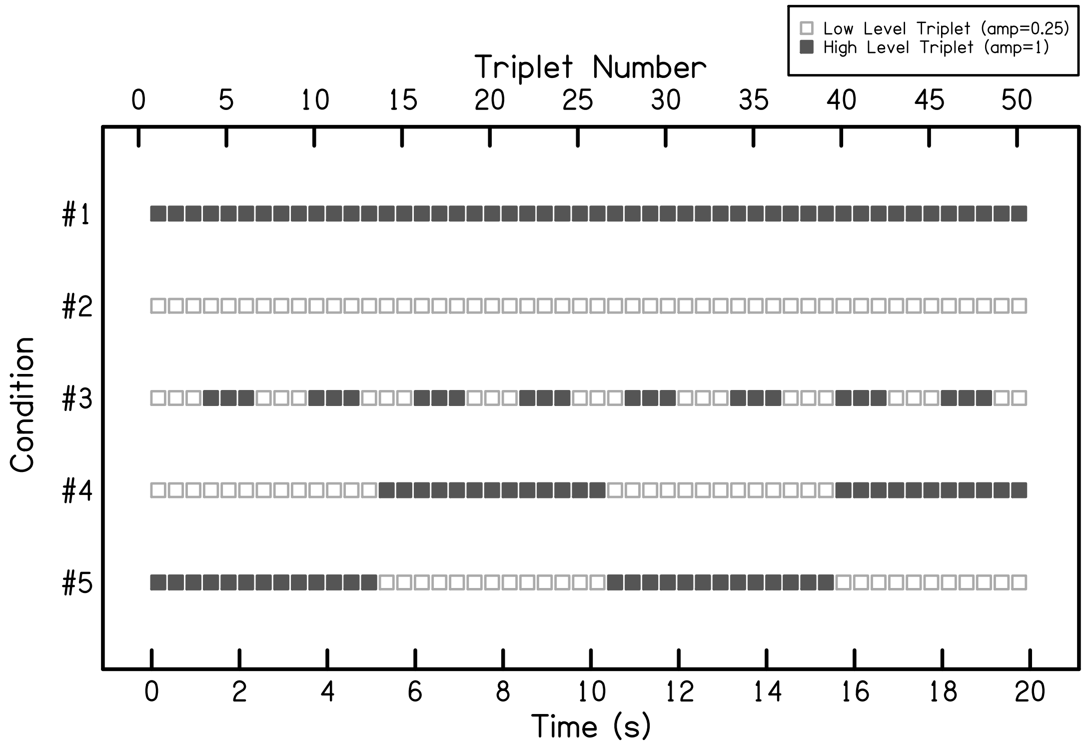

Figure 4.6: Illustration of the conditions in Experiment 4.

The hypotheses for the experiment were similar to those of Experiment 3. Prior to the completion of Experiment 3, it was expected that the rapid alternations in level every 3 triplets would cause suppression of build-up (as for Experiment 2) owing to the limited time for recovery between transitions. However, the results for Experiment 3 suggested that a substantial perceptual difference between the two constant cases may instead permit continual switching between two fixed percepts, (in Experiment 2, the integrated perception of the pure tone sequence and the more segregated perception of the tone dyad sequence).In this case a 'sawtooth' pattern of fluctuations would be evident, accompanied by an absence of build-up beyond the first few seconds.

It would also be anticipated that resetting would follow abrupt changes in the slowly alternating (13 triplet) cases. According to peripheral channelling accounts of build-up, the effects should be more pronounced in this experiment than in Experiment 3, because of the change in excitation pattern as sequences rise or fall in level. The findings of Rogers and Bregman (1998) and Roberts et al. (2008) would suggest an asymmetry in the response to rises and falls in level, with a fall in level resulting in substantially less resetting.

In general, a similar pattern of build-up would be anticipated for both constant high

TABLE 4.8: Three-way repeated measures ANOVA comparing constant only conditions i.e. High and Low Level conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**12.605**	**<0.001**	**0.736**
Condition	(1,11)	0.040	0.846	0.004
Time Interval	**(18,198)**	**75.882**	**<0.001**	**0.873**
Δf_{AB} × Condition	(2,22)	0.970	0.395	0.081
Δf_{AB} × **Time Interval**	**(36,396)**	**4.204**	**<0.001**	**0.227**
Condition × Time Interval	(18,198)	0.316	0.997	0.028
Δf_{AB} × Condition × Time Interval	(36,396)	1.353	0.089	0.110

and low level sequences. The broadening of auditory filters with increasing level would indicate that a higher level stimulus would tend to remain integrated slightly more than a low level stimulus (range = 12 dB), consistent with the findings of Rose & Moore (2000).

4.3.3 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As for Experiment 3, all conditions were presented during each of the 10 blocks within one session.

4.3.4 Results

The responses were analysed in the same way as those for Experiment 3. Again, three three-way repeated measures ANOVAs were conducted; the first compared the absolute effect of level using the two constant-level cases (Table 4.8, top left-hand panel of Figures 4.7-4.9), the second (Table 4.9) included the rapid alternating case with both constant cases (top right-hand panel of Figures 4.7-4.9), and the third (Table 4.10) compared the constant and slowly alternating conditions (bottom panels of Figures 4.7-4.9).

First, the comparison of constant cases revealed no significant differences in stream segregation between the high and low level sequences (p = 0.846, Table 4.8). Both conditions showed the same pattern of build-up and predicted increase in stream segregation with Δf_{AB} (p < 0.001). Neither the main effect of condition nor the interaction term for Condition × Time Interval were significant (p > 0.089, Table 4.8).

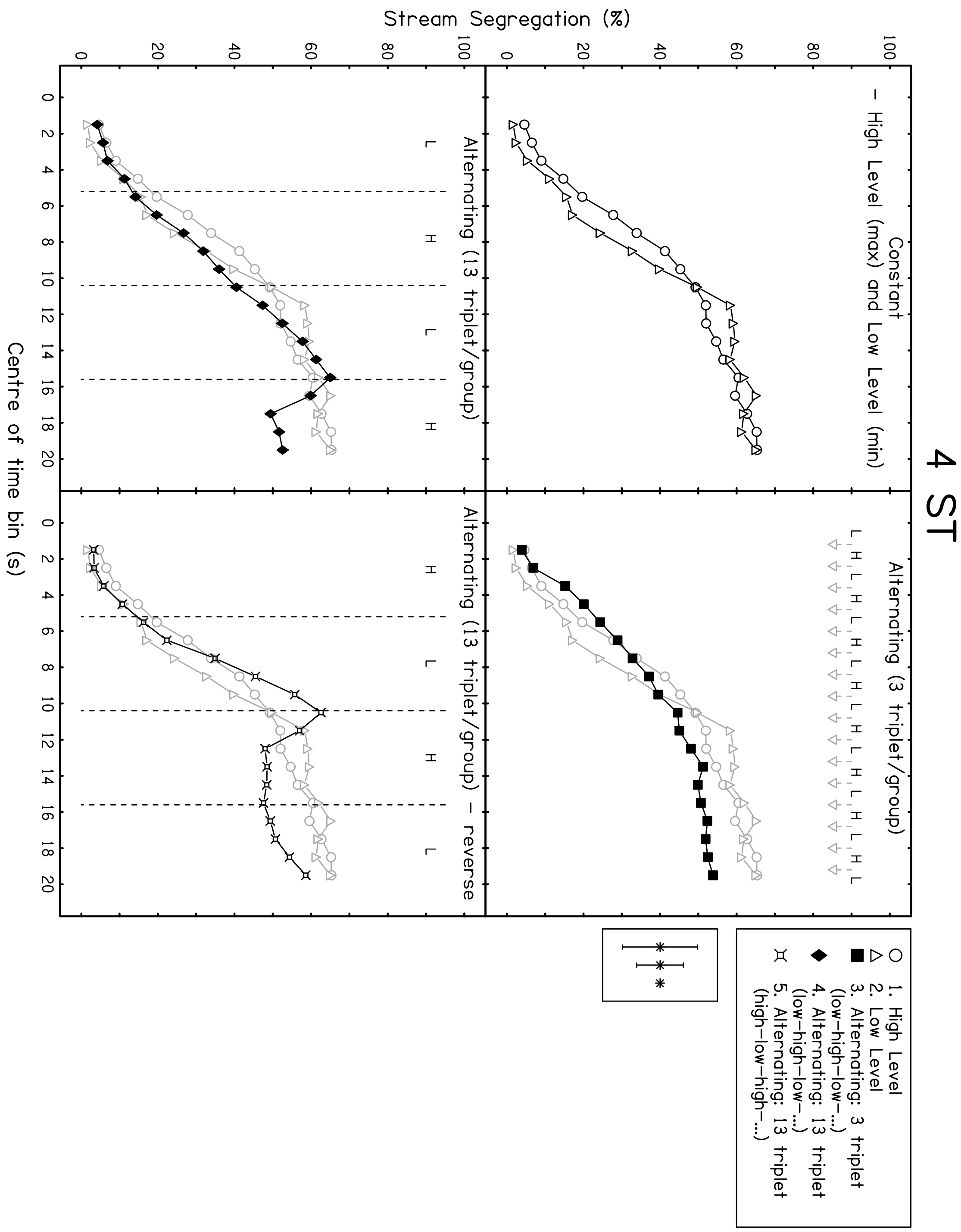

Figure 4.7: The stream segregation data averaged across listeners from Experiment 4 displaying the pattern of build-up over the 20 s test sequence for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

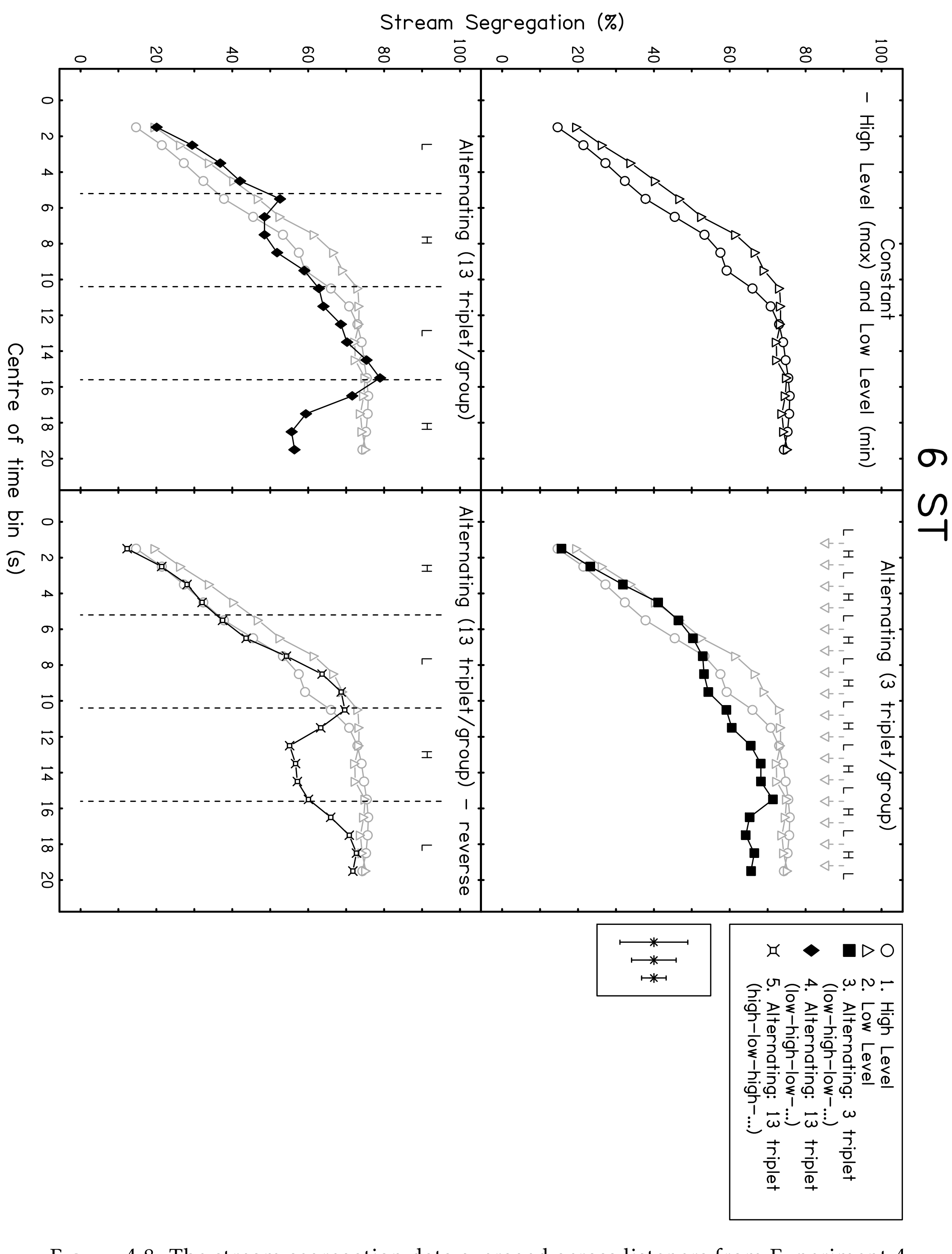

Figure 4.8: The stream segregation data averaged across listeners from Experiment 4 displaying the pattern of build-up over the 20 s test sequence for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

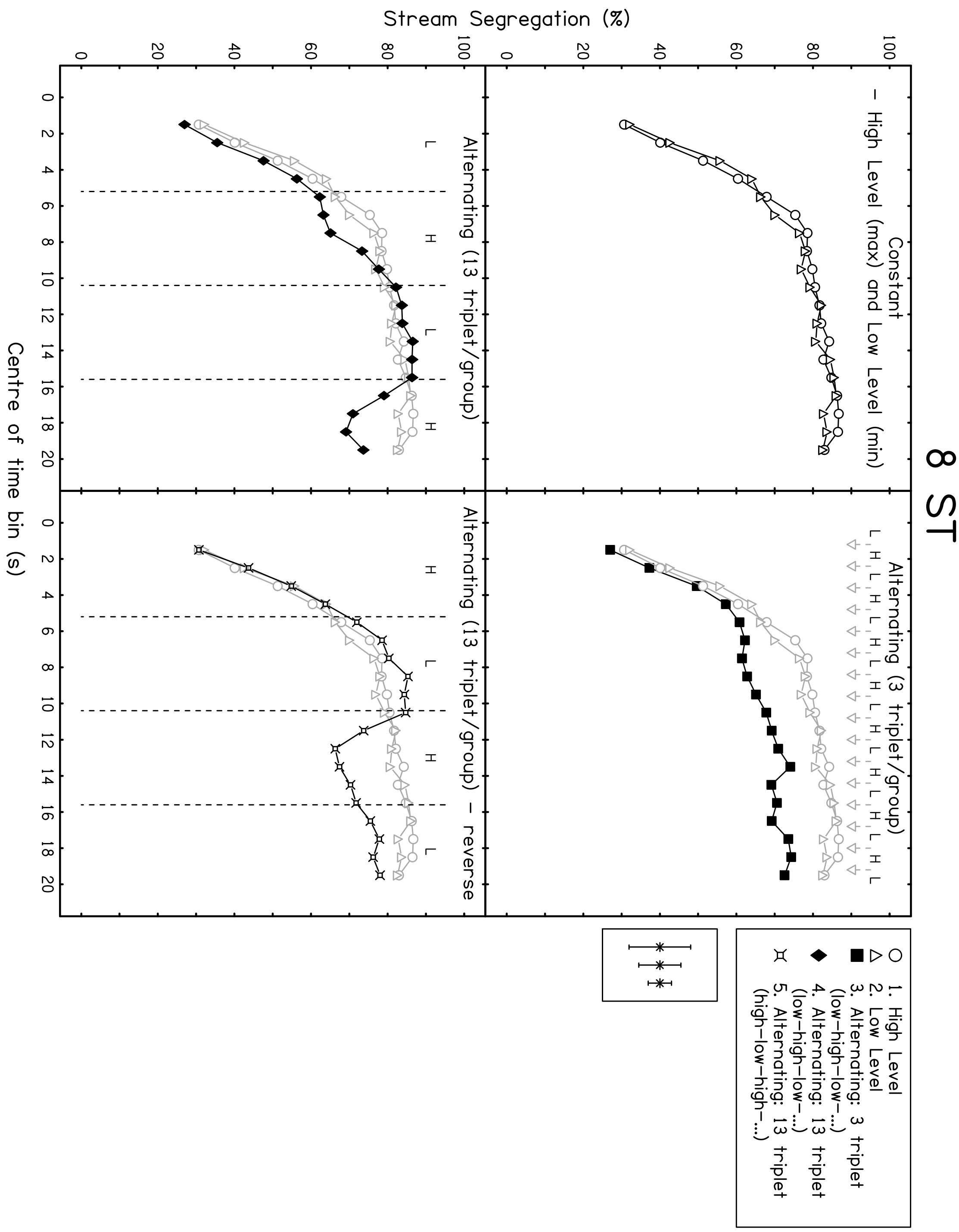

Figure 4.9: The stream segregation data averaged across listeners from Experiment 4 displaying the pattern of build-up over the 20 s test sequence for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

TABLE 4.9: Three-way repeated measures ANOVA comparing Constant and Rapidly Alternating conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**31.329**	**<0.001**	**0.784**
Condition	(2,22)	1.706	0.204	0.134
Time Interval	**(18,198)**	**67.804**	**<0.001**	**0.860**
Δf_{AB} × Condition	(4,44)	1.859	0.135	0.145
Δf_{AB} × **Time Interval**	**(36,396)**	**4.087**	**<0.001**	**0.271**
Condition × Time Interval	**(36,396)**	**1.746**	**0.006**	**0.137**
Δf_{AB} × Condition × Time Interval	(72,792)	1.115	0.247	0.092

TABLE 4.10: Three-way repeated measures ANOVA comparing Constant and Slowly Alternating conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**39.886**	**<0.001**	**0.784**
Condition	(3,33)	1.709	0.184	0.134
Time Interval	**(18,198)**	**80.865**	**<0.001**	**0.880**
Δf_{AB} × Condition	(6,66)	0.728	0.628	0.062
Δf_{AB} × **Time Interval**	**(36,396)**	**5.008**	**<0.001**	**0.313**
Condition × Time Interval	**(54,594)**	**4.131**	**<0.001**	**0.273**
Δf_{AB} × **Condition × Time Interval**	**(108,118)**	**1.465**	**0.002**	**0.118**

Second, the rapidly alternating case showed a pattern of build-up that was different from the constant cases. Although the initial rate of build-up was comparable (up to approx. 10 s), the segregation level reached by the rapidly alternating case tended to remain lower than that of the constant conditions, as reflected by the significant main effect of Time Interval ($p < 0.001$, Table 4.9) and significant interaction between Condition and Time Interval ($p = 0.006$).

Third, the slowly alternating conditions were observed to largely follow the same pattern as the constant conditions other than for the rising transitions (low-to-high level). Following a low-to-high level transition a drop in segregation occurred. This effect was least evident at the first transition point (5.2 s) and in that case was essentially absent when Δf_{AB}= 4 ST, owing to the limited scope available for resetting. The outcome of the final ANOVA was consistent with these observed differences in the plots. Condition was again not significant as a main effect ($p = 0.184$, Table 4.10) because of the similar pattern of build-up for most of the sequence duration. There was, however, a significant interaction between Condition and Time Interval ($p < 0.001$) driven by the fall in segregation resulting from abrupt rises in level. In contrast, falls in level (high-to-low level transitions) appeared to have little effect on subsequent

Table 4.11: Three-way repeated measures ANOVA, t=0 vs t=1

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	0.628	0.543	0.054
Direction (Rising vs. Falling)	**(1,11)**	**8.439**	**0.014**	**0.434**
Transition Number	(2,22)	1.727	0.201	0.136
Δf_{AB} × Direction	(2,22)	0.279	0.759	0.025
Δf_{AB} × Transition Number	(4,44)	1.022	0.406	0.085
Direction × Transition Number	**(2,22)**	**4.346**	**0.026**	**0.283**
Δf_{AB} × Direction × Transition Number	(4,44)	1.339	0.271	0.108

Table 4.12: Pairwise Comparisons, t=0 vs t=1
(*p*-values shown in black, mean difference scores in grey.)

		Direction of Level Change	
		Rising	Falling
Δf_{AB}	4 ST	**0.017**	0.068
		-6.8	*2.3*
	6 ST	**0.022**	0.855
		-9.2	*0.4*
	8 ST	**0.049**	0.881
		-7.2	*0.2*

judgements of stream segregation. The greater scope for resetting (due to faster rates of build-up) at greater frequency separations is reflected by the significant three-way interaction between Δf_{AB}, Condition and Time Interval ($p = 0.002$).

4.3.4.1 Effects of Δf_{AB}, Condition and Time Interval

The transient effects of single abrupt changes in the two slower alternating conditions were explored further using the methods described for Experiment 3. Again, the transitions were grouped so that the effects of the two types of transition—rising (low-to-high level) and falling (high-to-low level)—could be compared. This involved grouping together the first and third transitions from Condition 4 with the second from Condition 5 (rising case), and the second transition from Condition 4 with the first and third from Condition 5 (falling case). Figure 4.10 summarises these data plotted over the 20-s sequence duration for each Δf_{AB}. As previously, the data were then analysed twice: the first three-way repeated measures ANOVA was run on 1-s intervals pre- and post-transition (see Tables 4.11 and 4.12), and the second was extended to include 2-s pre- and post-transition (Tables 4.13 and 4.14).

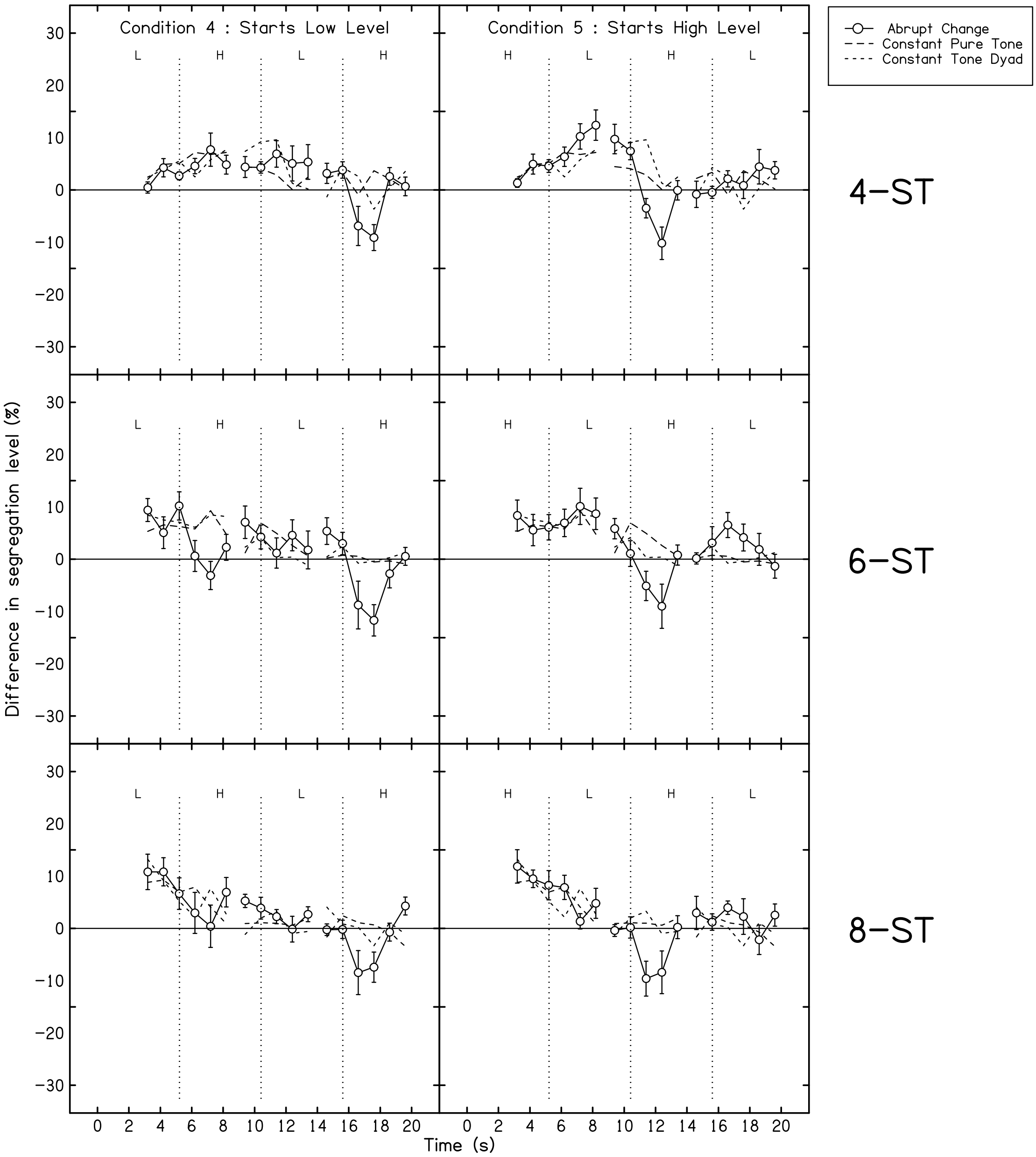

Figure 4.10: Results from Experiment 4 derived from the difference calculations.This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n=n-1, where n=current time-bin) and plotting the value for the the corresponding time-bin (n).

Table 4.13: Three-way repeated measures ANOVA, average(t=-1, t=0) vs average(t=1, t=2)

Factor/ Factor Interaction	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	1.313	0.289	0.107
Direction (Rising vs. Falling)	**(1,11)**	**13.457**	**0.004**	**0.550**
Transition Number	(2,22)	1.378	0.273	0.111
Δf_{AB} × Direction	(2,22)	2.491	0.106	0.185
Δf_{AB} × Transition Number	(4,44)	2.542	0.054	0.187
Direction × Transition Number	(2,22)	2.838	0.080	0.205
Δf_{AB} × Direction × Transition Number	(4,44)	1.460	0.230	0.117

Table 4.14: Pairwise Comparisons, average(t=-1, t=0) vs average(t=1, t=2) (*p*-values shown in black, mean difference scores in grey.)

		Direction of Level Change	
		Rising	Falling
Δf_{AB}	4 ST	**0.005**	0.260
		-12.1	*3.1*
	6 ST	**0.002**	0.738
		-17.8	*12.6*
	8 ST	**0.016**	0.075
		-12.4	*-2.9*

As expected, both ANOVAs showed significant main effects of Δf_{AB} and Time Interval ($p < 0.001$, in all cases), and a significant interaction between them ($p < 0.001$, in all cases). The outcomes of these ANOVAs are considered in turn.

There was a clear asymmetry between the effects of rising and falling level, shown by the significance of direction for the first epoch and second epoch ANOVAs, ($p = 0.014$, Table 4.11, and $p = 0.004$, Table 4.13). Across all Δf_{AB}s the rising-level transition resulted in a substantial negative peak within the following 2 s. At the time of the abrupt change, the difference in segregation level tended to remain within the 0-5% range, indicating that limited build-up was occurring at that point. In the following 1-s interval, the difference in segregation level fell significantly for all Δf_{AB} ($p < 0.05$, Table 4.12). The fall in segregation level became larger over the subsequent time interval, as is evident in the increasing significance and mean difference scores for the extended 2-s analysis ($p < 0.02$, Table 4.14). Given the increased scope for resetting at higher frequency separations, it is notable that the extent of the fall in segregation increased between the 4- and 6-ST cases, but the effect was slightly less pronounced for 8-ST transitions (see Table 4.14). Subsequent to the second interval post-transition, difference scores rapidly returned to 0 (at approximately 3 s).

The significant interaction between the direction of the transition and the transition number was evident in the only the first epoch analysis (p=0.026, Table 4.11) and not the second (p=0.080, Table 4.13). This could be because the rising level transitions have a slower resetting effect if occurring earlier on in the tone sequence.The falling-level transitions had no clear discernible effect; these transitions were not associated with significant effects on the rate of change of stream segregation.

4.3.5 Discussion

As hypothesised, the high- and low-level constant cases displayed no significant differences. For both cases, the expected effects of frequency separation and build-up of segregation were clearly evident. Whilst a small but significant suppression of build-up resulted from the rapid abrupt changes in the alternating (3 triplet) case, the 'sawtooth' pattern observed in Experiment 3 is not present here.

The pattern of build-up for this case, more strongly resembled that of the corresponding case in Experiment 2 (ITD changes). This more subtle effect of rapid abrupt changes may be a consequence of the smaller contrast between the two constant cases, and limited scope for alternation between the two percepts. Alternatively, it could be a result of continuous resetting occurring in response to every change. As proposed in the previous chapter, it may be that a correlated rise or fall in level is considered the variation in a signal from a single source, rather than the change from one sound source to another. This information may be increasing the tendency for the percept to remain segregated and lowering the rate of build-up accordingly.

Whilst the transitions in level for the slower alternating (13 triplet case) did not produce effects as striking as those for the corresponding cases in Experiment 3, rising level transitions clearly produced a significant partial resetting in the build-up of stream segregation. Falls in level, however showed no discernible change in the build-up of segregation. This asymmetry is generally consistent with the observations of Rogers and Bregman (1998) and Roberts et al. (2008), who suggest that a rise in level is more likely to cue the presence of a new sound source in the environment whereas a fall in level is less likely to do so.

The results of Experiment 4 suggest that a maintained 12 dB difference in level has little, if any, effect on the build-up of streaming. However, abrupt changes of 12 dB can have significant effects on stream segregation. Specifically, a rise in level can cause partial resetting and rapid alternations in level can cause suppression of build-up. Although a change in level of 12 dB does affect the excitation pattern generated by a signal, this difference remains the same regardless of the direction of the change and cannot be accounted for by a simple peripheral channelling account.

4.4 General Discussion

The results of Experiments 3 and 4 clearly demonstrate that a sudden change in acoustical properties can produce a substantial change in stream segregation even when there is no significant change in the pattern of peripheral excitation for a given sequence of sounds. This outcome suggests that any perceptually salient change can not only cause resetting of build-up, but in some cases an extremely segregated percept.

It is notable that many of the properties explored with respect to the dynamics of resetting—e.g., frequency—not only cause changes in excitation pattern but are also highly noticeable. Yet the perceptual salience of a change (largely due to the difficulty in quantifying such a property) has rarely been considered when discussing the factors influencing the build-up and resetting of segregation.

The less striking effect of level changes in comparison with timbre changes can be explained to some extent from this functional perspective. A single sound source within a natural listening environment could be expected to vary in level by up to 6 dB, as it moves around in space. However the timbre of this signal could be expected to remain reasonably fixed. Therefore a sudden change in timbre is highly likely to be considered the stopping of a signal originating from one source with the onset of a new signal produced by a distinct source.

An alternative explanation, briefly referred to earlier, is that the patterns of stream segregation for the less frequent abrupt alternations in level and timbre arise from the slow adaptation of neural populations tuned to temporal regularity of the stimulus (which would differ much more for the altered temporal envelope of a tone dyad vs pure tone, than for a change in level). The response to sudden changes would be consistent with a slower subtractive adaptation of these neurons. Though less commonly discussed with respect to auditory neurons, a subtractive process has been proposed as a mechanism for light adaptation in studies of visual perception (Geisler, 1983; Hayhoe et al. 1991). Subtractive adaptation acts to reduce the baseline signal in response to a constant stimulus; a proportion of the signal is subtracted from itself so that the amplitude of the response signal falls with time.

This would suggest that build-up occurs in response to the falling amplitude in the response of adjacent, overlapping neural populations. As the response continues to fall, the degree of overlap between the two populations would also fall resulting in an increased tendency towards a segregated percept. In the case of a shift from pure tone to dyad, the falling amplitude of the signal causes a dramatic overshoot in segregation level (as a result of this shift of the starting level to a higher perceptual level). Resetting or undershoot would therefore occur with a shift in the opposite direction resulting from the tone dyad to pure tone change.

Chapter 5

Correlated and Anti-Correlated Abrupt Changes in the Level of Tone Subsets

5.1 Introduction

The experiments presented earlier in the thesis have explored the effect of correlated changes in stimulus properties on stream segregation, in other words the effect of changing both subsets of sounds (the 'A'- and the 'B'-tones) in the same way and at the same time. In general, these experiments have shown that a correlated abrupt change in stimulus properties can produce a substantial change in stream segregation (typically a resetting of the build-up of streaming, but also in some circumstances an 'overshoot', as evident in Experiment 3) even when there is no accompanying change in the peripheral excitation pattern. Explanations have tended to focus on models of neural adaptation although, as proposed in the previous chapter, a correlated change in stimulus properties could be considered as indicating the varying of a signal originating from a single source.

Consistent with earlier studies (Rogers and Bregman, 1998; Roberts et al., 2008), Experiment 4 demonstrated that abrupt falls in level had only a limited impact on the build-up of segregation. In contrast, a rise in level resulted in partial resetting. Rogers and Bregman (1998) proposed that this could be due to the increased likelihood that rises in level cue the presence of a new sound source in the environment whereas falls in level are less likely to do so. The two experiments in this chapter followed on from Experiment 4 to examine further the hypothesis that correlated level shifts of tone subsets of equal magnitude in the same direction would cue origin from a single source. To do so, the effects of correlated and anti-correlated changes were measured.

The effects of level differences between tone subsets within constant sequences were first explored by Van Noorden (1975), who established that a difference exceeding 3 dB increased the tendency to perceive two streams rather than one. Hartmann and Johnson (1991) used an 8-dB level difference between the melody and interleaved distractor tones. Whilst this aided segregation of the target melody from the distractor tones, performance in the melody detection task was not as good as cases where properties affecting excitation pattern more strongly were used to differentiate the target tones from the distractor sounds. Hartmann and Johnson (1991) argued that the limited differences in excitation pattern generated by an 8-dB level difference accounted for the weaker effect in comparison with spectral properties.

The level differences between subsets in the experiments presented within this chapter, were accordingly fixed at 6 dB to limit alterations in the pattern of peripheral channelling whilst producing a perceptually salient rise or fall in stimulus level.

The following two experiments used 20-s-long 'ABA-' sequences to investigate the effect of correlation in level changes across 'A' and 'B' tone subsets on the build-up and resetting of streaming. Experiment 5 used 'LHL-' triplets to explore the effects of three aspects of tone level. First, whether a constant difference in level between the 'A' and 'B' tones would affect the extent of stream segregation. Second, whether correlated and anti-correlated changes in the levels of 'A' and 'B' tones would produce predictable changes in streaming and, third, whether the direction of the level change would have an influence on the effect. Experiment 6 compared 'LHL-' and 'HLH-' triplet structures to determine if separate tone subsets exerted variable effect on streaming.

5.2 Experiment 5: Correlated and Anti-Correlated Level Changes

5.2.1 Method

The method and procedure for this experiment were as described in the General Methods (Chapter 2). Listeners were required to continuously monitor the 'ABA-' sequence and indicate whether it was perceived as either integrated or segregated.

5.2.2 Conditions and Hypotheses

As for Experiment 4 (Chapter 4), level was calculated relative to a baseline of 70 dB SPL. Low-level sounds were set to 3 dB below the baseline and high-level sounds were set to 3 dB above, so the output ranged between 67 and 73 dB SPL. The 'A' tones were set at 1 kHz and the 'B' tones were adjusted according to Δf_{AB}.

The conditions below are summarised in Figure 5.1:

1. *Constant Amplitude – max:* All triplets are 3 dB above baseline (high).
2. *Constant Amplitude – min:* All triplets are 3 dB below baseline (low).
3. *Constant difference – 'A' = high & 'B' = low.*
4. *Constant difference – 'A' = low & 'B' = high.*
5. *Correlated alternations – high first:* Both 'A' and 'B' tones change from high → low (& v/v) every 4 s (10 triplets).
6. *Correlated alternations – low first:* As Condition 5, but reversed order.
7. *Anti-correlated alternations – 'A' high first:* 'A' and 'B' tones switch in opposite directions every 4 s, high → low (& v/v). Initially, 'A' = high & 'B' = low.
8. *Anti-correlated alternations – 'B' high first:* As Condition 7, but reversed order.

It was hypothesised that correlated alternations would cause resetting of stream segregation as they cue a common origin for the 'A' and 'B' subsets. In contrast,

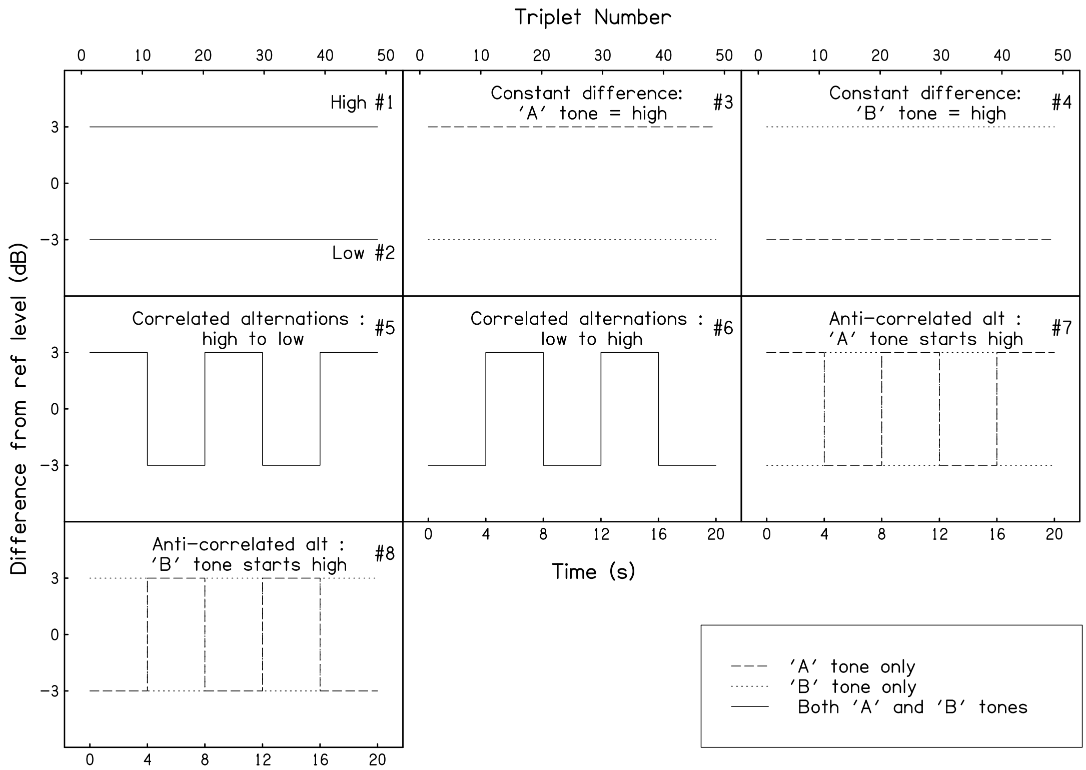

Figure 5.1: Experiment 5 conditions

anti-correlated changes would increase segregation (causing overshoot) as they cue a different origin for each subset. Consistent with Experiment 4, rises in level would be expected to cause greater resetting than falls (cf. Rogers & Bregman, 1998).

5.3 Results

The results of Experiment 5 were first analysed with four, three-way repeated measures ANOVAs and the corresponding pairwise comparisons. The first ANOVA, summarised in Table 5.1, compared the constant high and low cases (top, left-hand panel of Figures 5.2-5.4). The second, summarised in Table 5.2, compared the average of the constant same-level cases with the constant difference cases (top, left-hand panel of Figures 5.2-5.4). The third (Table 5.4) compared the constant-same and correlated level-change conditions (top panels of Figures 5.2-5.4), whilst the fourth (Table 5.6) compared the constant difference and anti-correlated cases (bottom panels of Figures 5.2-5.4).

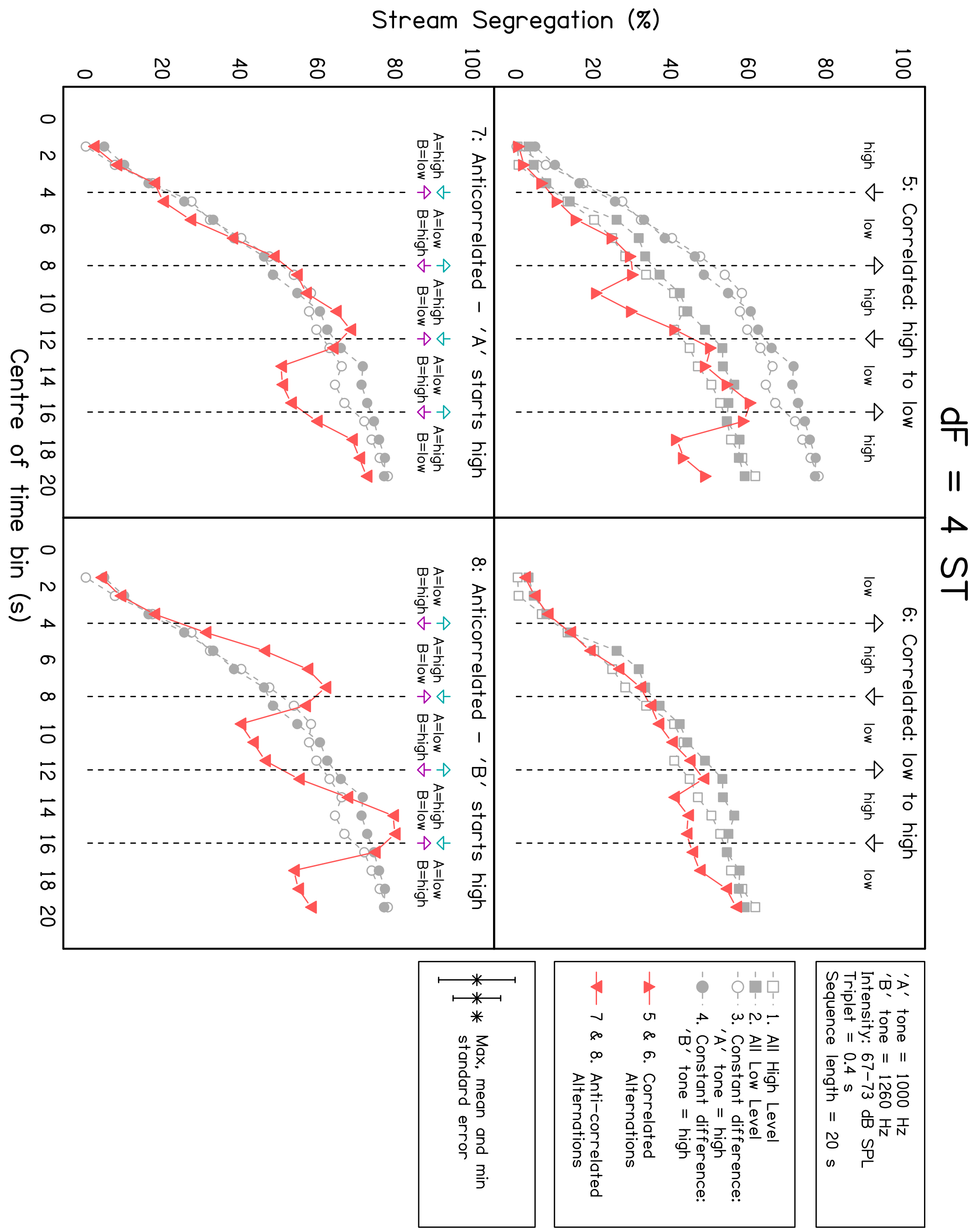

Figure 5.2: The stream segregation data averaged across listeners from Experiment 5 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

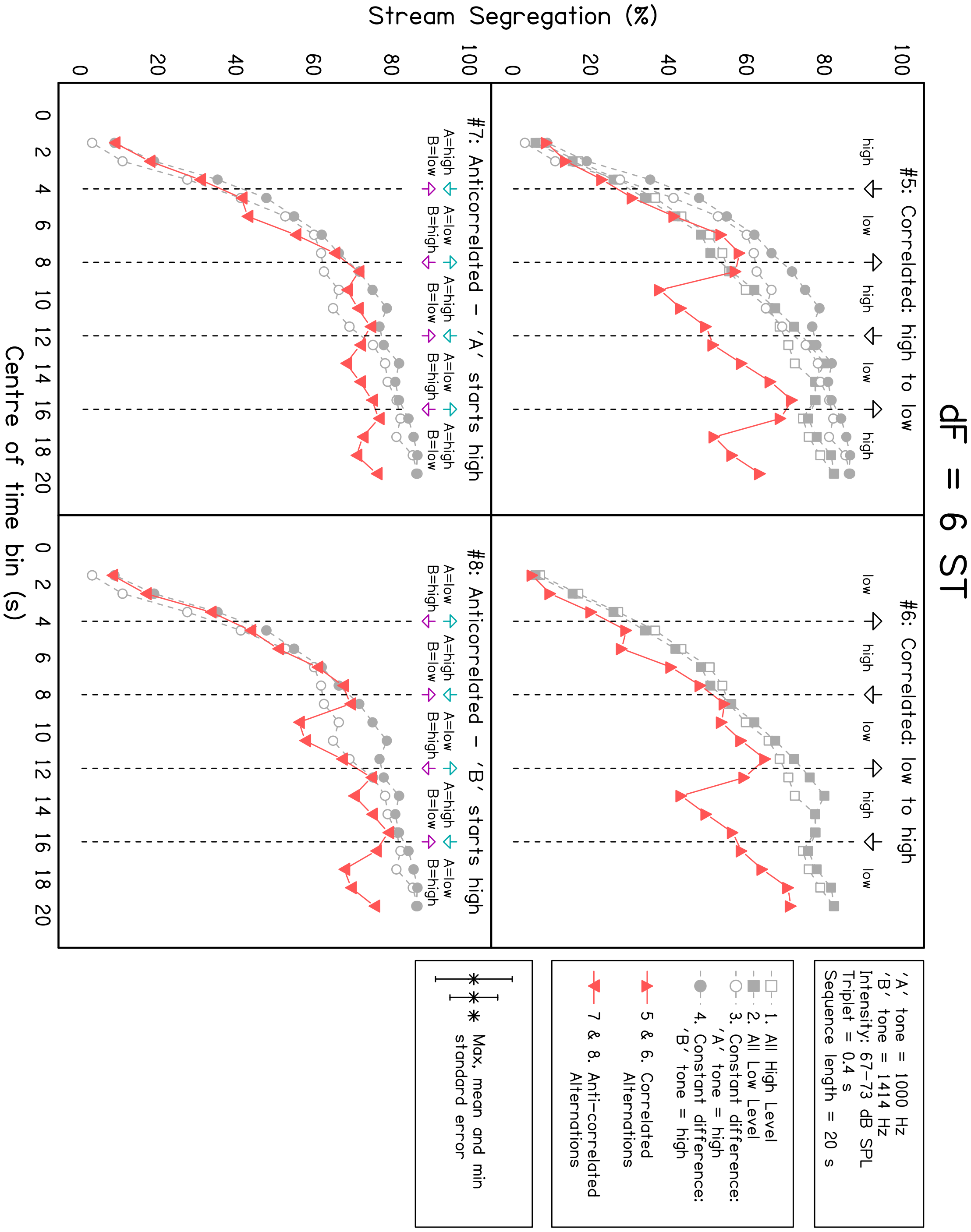

Figure 5.3: The stream segregation data averaged across listeners from Experiment 5 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

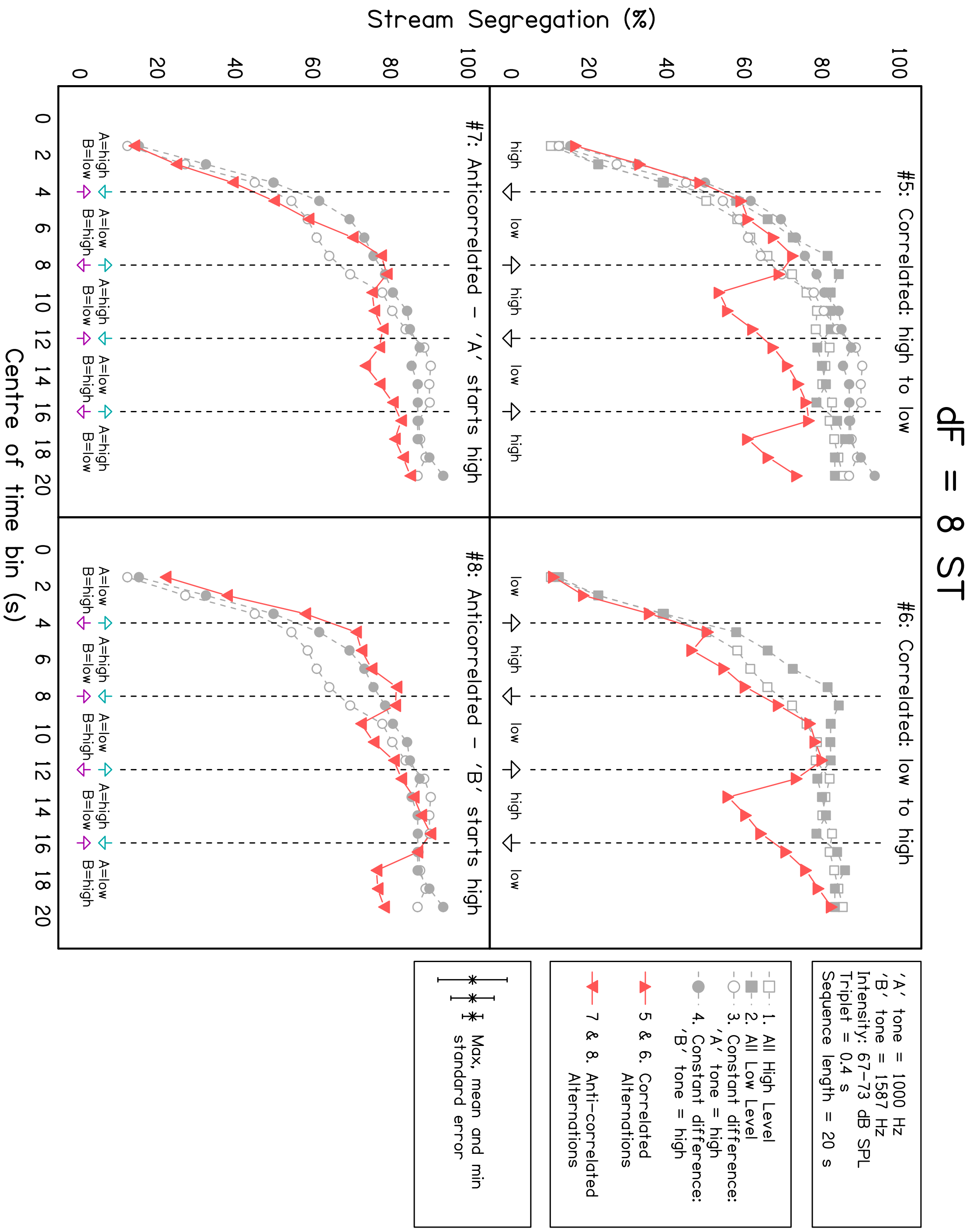

Figure 5.4: The stream segregation data averaged across listeners from Experiment 5 displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

TABLE 5.1: Three-way repeated measures ANOVA comparing constant all high and all low level conditions (A & B tones at the same level).

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**47.762**	**<0.001**	**0.813**
Condition	(1,11)	1.505	0.246	0.120
Time Interval	**(18,198)**	**71.693**	**<0.001**	**0.867**
Δf_{AB} × Condition	(2,22)	0.158	0.855	0.014
Δf_{AB} × **Time Interval**	**(36,396)**	**4.524**	**<0.001**	**0.291**
Condition × Time Interval	(18,198)	0.635	0.869	0.055
Δf_{AB} × Condition × Time Interval	(36,396)	0.852	0.715	0.072

TABLE 5.2: Three-way repeated measures ANOVA comparing the average of constant all-same and constant all-different conditions.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**34.474**	**<0.001**	**0.758**
Condition	**(1,11)**	**11.524**	**0.006**	**0.512**
Time Interval	**(18,198)**	**73.541**	**<0.001**	**0.870**
Δf_{AB} × **Condition**	**(2,22)**	**5.566**	**0.011**	**0.336**
Δf_{AB} × **Time Interval**	**(36,396)**	**4.211**	**<0.001**	**0.277**
Condition × Time Interval	(18,198)	1.363	0.153	0.110
Δf_{AB} × **Condition** × **Time Interval**	**(36,396)**	**2.655**	**<0.001**	**0.194**

TABLE 5.3: Pairwise Comparison of means of constant all-same and constant all-different conditions.

[I]	[J]	Mean Difference [I-J] (%)	Std. Error (%)	*p*
Average of constant A&B same cases	**Average of constant A&B different cases**	**-7.9**	**23.4**	**0.006**

TABLE 5.4: Three-way repeated measures ANOVA comparing constant A&B same and correlated change conditions.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**44.887**	**<0.001**	**0.803**
Condition	**(3,33)**	**8.776**	**<0.001**	**0.444**
Time Interval	**(18,198)**	**66.961**	**<0.001**	**0.859**
Δf_{AB} × Condition	(6,66)	1.022	0.491	0.085
Δf_{AB} × **Time Interval**	**(36,396)**	**5.156**	**<0.001**	**0.319**
Condition × Time Interval	**(54,594)**	**3.268**	**<0.001**	**0.229**
Δf_{AB} × **Condition** × **Time Interval**	**(108,1188)**	**1.262**	**0.042**	**0.103**

TABLE 5.5: Pairwise Comparison of means of same-level and correlated-change conditions.

[I]	[J]	Mean Difference [I-J] (%)	Std. Error (%)	p
All high	All low	-2.5	2.0	0.246
	Corr. change (5)	**6.2**	**2.1**	**0.014**
	Corr. change (6)	**6.5**	**2.1**	**0.010**
All low	All high	2.5	2.0	0.246
	Corr. change (5)	**8.7**	**2.3**	**0.003**
	Corr. change (6)	**9.0**	**2.5**	**0.005**
Corr. change (5)	**All high**	**-6.2**	**2.1**	**0.014**
	All low	**-8.7**	**2.3**	**0.003**
	Corr. change (6)	2.4	1.7	0.891
Corr. change (6)	**All high**	**-6.5**	**2.1**	**0.010**
	All low	**-9.0**	**2.5**	**0.005**
	Corr. change (5)	-2.4	1.7	0.891

TABLE 5.6: Three-way repeated measures ANOVA comparing constant A&B difference and anti-correlated change conditions.

Factor	df	F	p	η_p^2
Δf_{AB}	**(2,22)**	**19.0**	**<0.001**	**0.634**
Condition	(3,33)	1.423	0.254	0.115
Time Interval	**(18,198)**	**61.440**	**<0.001**	**0.848**
Δf_{AB} × Condition	(6,66)	0.611	0.491	0.053
Δf_{AB} × Time Interval	(36,396)	3.165	0.720	0.223
Condition × Time Interval	**(54,594)**	**1.963**	**<0.001**	**0.151**
Δf_{AB} × **Condition × Time Interval**	**(108,1188)**	**1.633**	**<0.001**	**0.121**

5.3.1 Effects of Δf_{AB}, Condition and Time Interval

As expected, the established pattern of build-up was present across all conditions along with the increased overall level of segregation at larger Δf_{AB}; all four ANOVAs showed significant main effects of Time Interval ($p < 0.001$) (see Appendix for pairwise comparison tables of Δf_{AB} and Time Interval). Increases in Δf_{AB} also caused acceleration of the rate of build-up, as can be observed in the significant interaction term for Δf_{AB} × and Time Interval in all four ANOVAs ($p < 0.001$).

5.3.1.1 Constant level sequences

As for Experiment 4, an absolute level difference of 6 dB between the all-high and all-low level sequences produced no significant difference in listener percept. Both conditions showed the same pattern of build-up, and the expected increase in the extent of segregation with Δf_{AB}. Accordingly, neither the main effect of Condition nor any interaction term involving Condition were significant ($p > 0.05$, Table 5.1).

Establishing a constant 6-dB difference between the 'A' and 'B' tone subsets resulted in a significantly elevated overall segregation level in comparison with the all-same constant cases, as shown in the second ANOVA which compared the means of the constant all-different and all-same cases ($p = 0.006$, mean difference = 7.9 percentage points, Table 5.3). However the rate of build-up remained similar for both cases (Condition × Time Interval $p = 0.153$, Table 5.2). The difference in overall segregation between the the constant all-different and all-same cases declined with increasing Δf_{AB}, owing to the limited scope for increased segregation at 6 and 8 ST. These outcomes are reflected in the significant interactions between Δf_{AB} and Condition ($p = 0.011$), and between Δf_{AB}, Condition and Time Interval ($p < 0.001$).

5.3.1.2 Correlated changes in level

The third ANOVA compared the constant-same and correlated-change conditions, revealing a highly significant effect of Condition ($p < 0.001$, Table 5.4). Visible in the patten for the correlated change cases (top, left-hand panel of Figures 5.2-5.4) was a fall in the extent of segregation subsequent to a rising transition. Pairwise comparisons demonstrated that correlated changes also resulted in a reduction in the overall level of segregation ranging between 6.2 and 9.0 percentage points (p = 0.03 to 0.014, Table 5.5), reflecting the drops in segregation level in response to correlated rises in level (from low to high level). Rising transitions occurring later in the sequence produced stronger resetting as there had been adequate time for build-up of a higher segregation level to occur (shown in the significant interaction between Condition × Time Interval, $p < 0.001$). The faster rate of build-up and higher segregation levels at higher Δf_{AB}s provided increased scope for resetting in response to rising transitions, which accounts for the significant interaction terms between Δf_{AB} and Time Interval ($p < 0.001$), and between Δf_{AB}, Condition, and Time Interval ($p = 0.042$).

5.3.1.3 Anti-correlated changes in level

The fourth ANOVA compared the constant-difference and anti-correlated change conditions. In this case, Condition did not demonstrate a significant main effect ($p = 0.254$, Table 5.6). Despite visible drops in segregation level following the anti-correlated Falling 'A'/Rising 'B' tone transitions at 4- and 6-ST separations (bottom panels of Figures 5.2-5.4), there was no significant interaction between Δf_{AB} × Condition ($p = 0.720$, Table 5.6). As this interaction is considered across time interval, it is potentially not significant because in addition to the A↓B↑ transition causing resetting, 'overshoot' results from the A↑B↓ change. When averaged over time, these transient effects are likely to have made little difference to the overall extent of segregation. Notably both Condition × Time Interval and Δf_{AB} × Condition × Time Interval term were significant ($p < 0.001$, Table 5.6). The significant interaction between Condition and interval appears to arise from the differences in the shape of the profiles following A↓B↑ and A↑B↓ changes. As Δf_{AB} was increased the effects of transitions appear to fall, resulting in the significant three-way interaction term. In direct contrast to the correlated change case, where increasing Δf_{AB} caused resetting to become more prominent, the effect of anti-correlated changes (both resetting and overshoot) weakened at higher Δf_{AB}s.

5.3.2 The effect of abrupt transitions on the rate of change of the extent of segregation

Although the ANOVAs described earlier demonstrated the significant effect of correlated and abrupt changes in level, they did not reveal the influence of the direction of changes on segregation for either correlated or anti-correlated abrupt changes. In accordance with the methods described in Chapter 2, the raw data were re-analysed. Each condition was first re-analysed to centre the time bins on the abrupt changes occurring every 4 s (i.e., the initial time-bin was 0.5-1.5 s). The reanalysed results were used to generate the change in segregation level over time [(n-(n-1) time bins].

Figures 5.5-5.7 show these data plotted over the 20-s sequence duration for each Δf_{AB}. To allow the influence of transition number to be explored in the associated analyses, transitions of the same type were grouped together. The groupings used were as follows: the correlated rising transitions (the first, third, and fifth transitions from condition 5 with the second and fourth transitions from condition 6, denoted A↑B↑), the correlated falling transitions (the second and fourth from condition 4 with the first, third, and fifth from condition 5, denoted A↓B↓), the anti-correlated 'B' rising/ 'A' falling transitions (the first, third, and fifth transitions from condition 7 with the second and fourth transitions from condition 8, denoted B↑A↓) and the anti-correlated 'B' falling/ 'A' rising transitions (the second and fourth from condition 7 with the first, third, and fifth from condition 8, denoted B↓A↑). First, each abrupt change was tested to establish whether or not it produced a significant change in the extent of segregation. The data were then analysed for correlated and anti-correlated conditions twice: the first and second three-way repeated measures ANOVAs were run on 1-s intervals pre- and post-transition (first epoch analysis, see Tables 5.7 and 5.8). The third and fourth were extended to include 2-s pre and post transition (second epoch analysis, see Tables 5.9 and 5.10).

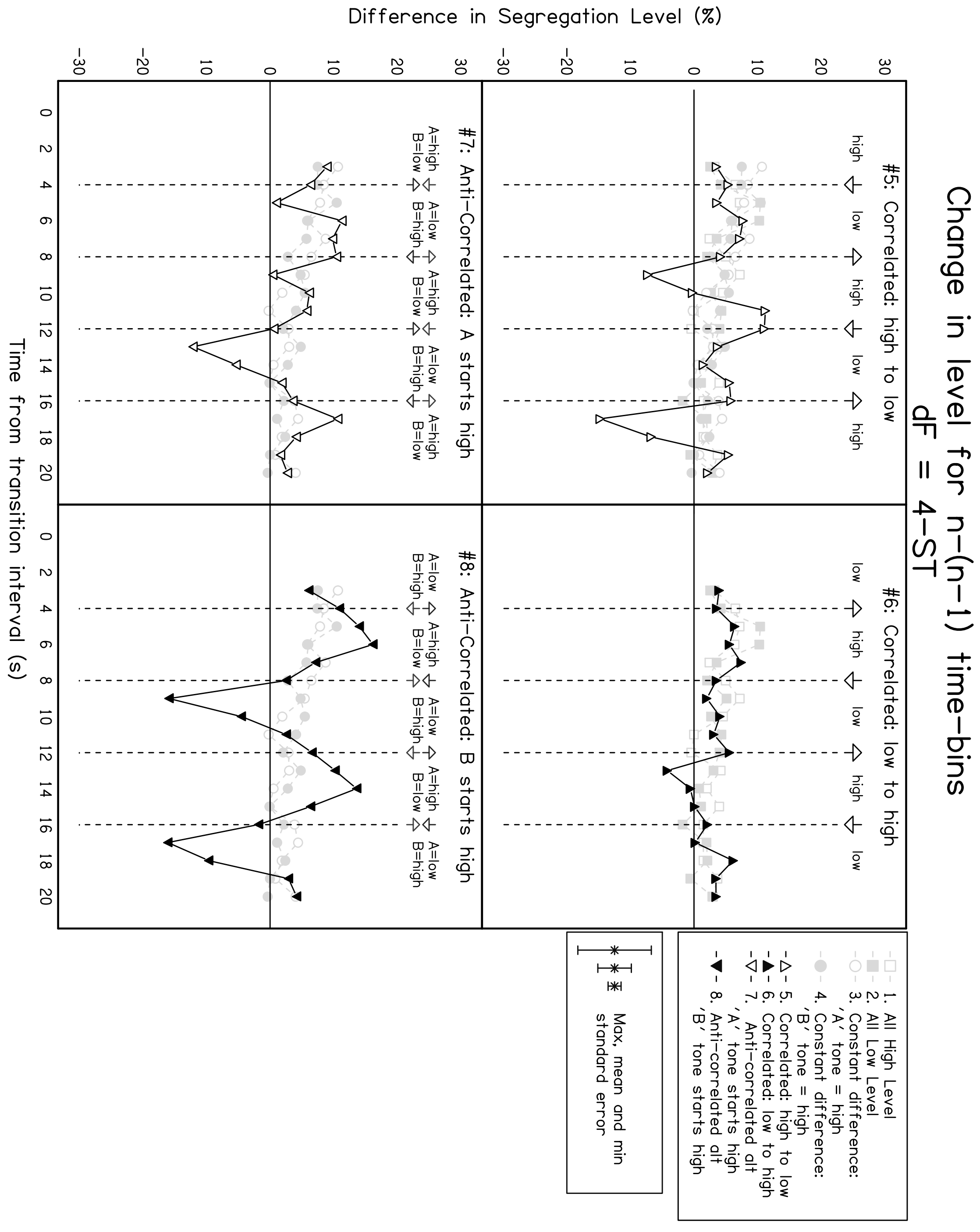

FIGURE 5.5: Results from Experiment 5 derived from the difference calculations for a Δf_{AB} of 4 ST. This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the the corresponding time-bin (n).The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

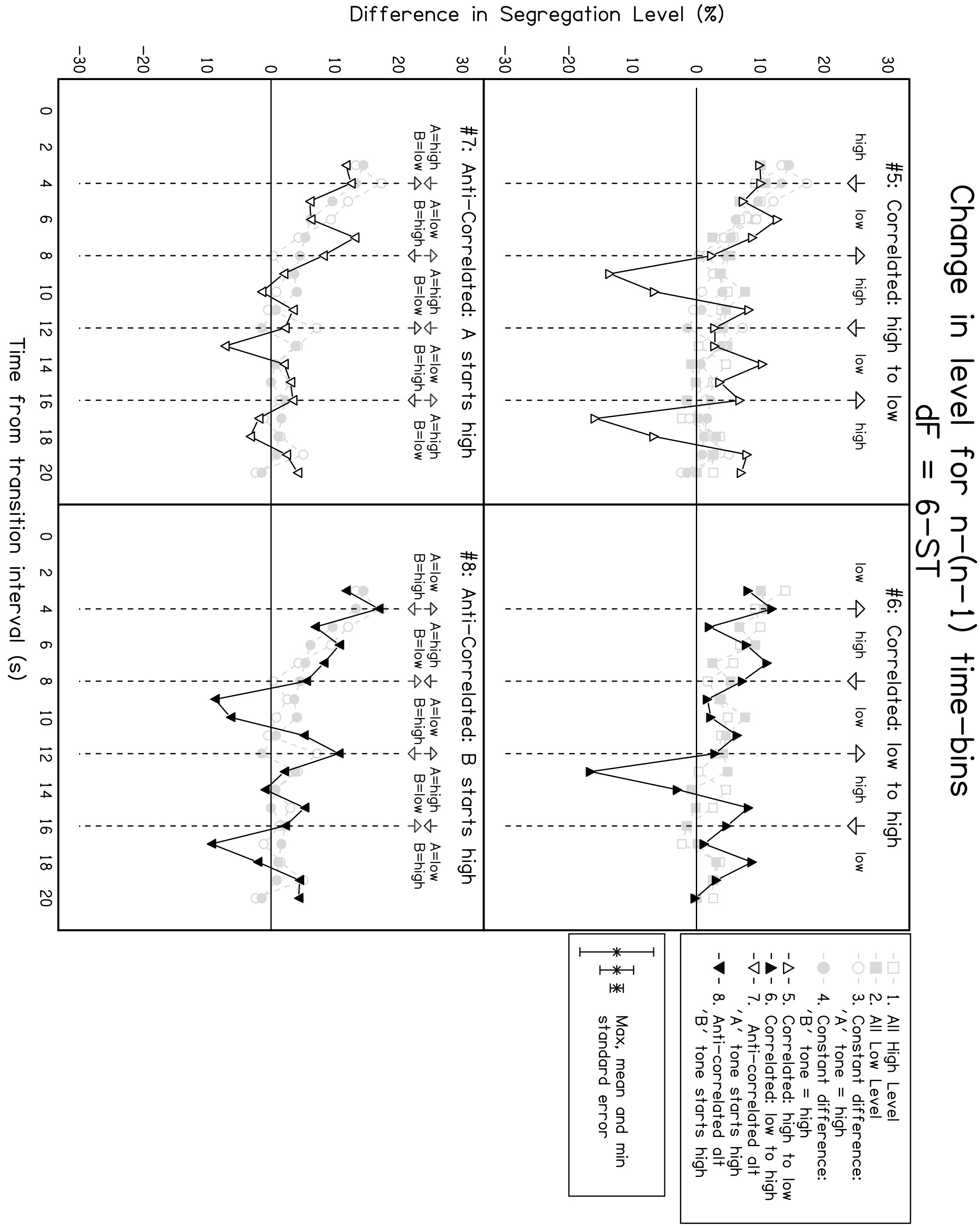

Figure 5.6: Results from Experiment 5 derived from the difference calculations for a Δf_{AB} of 6 ST. This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the the corresponding time-bin (n).The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

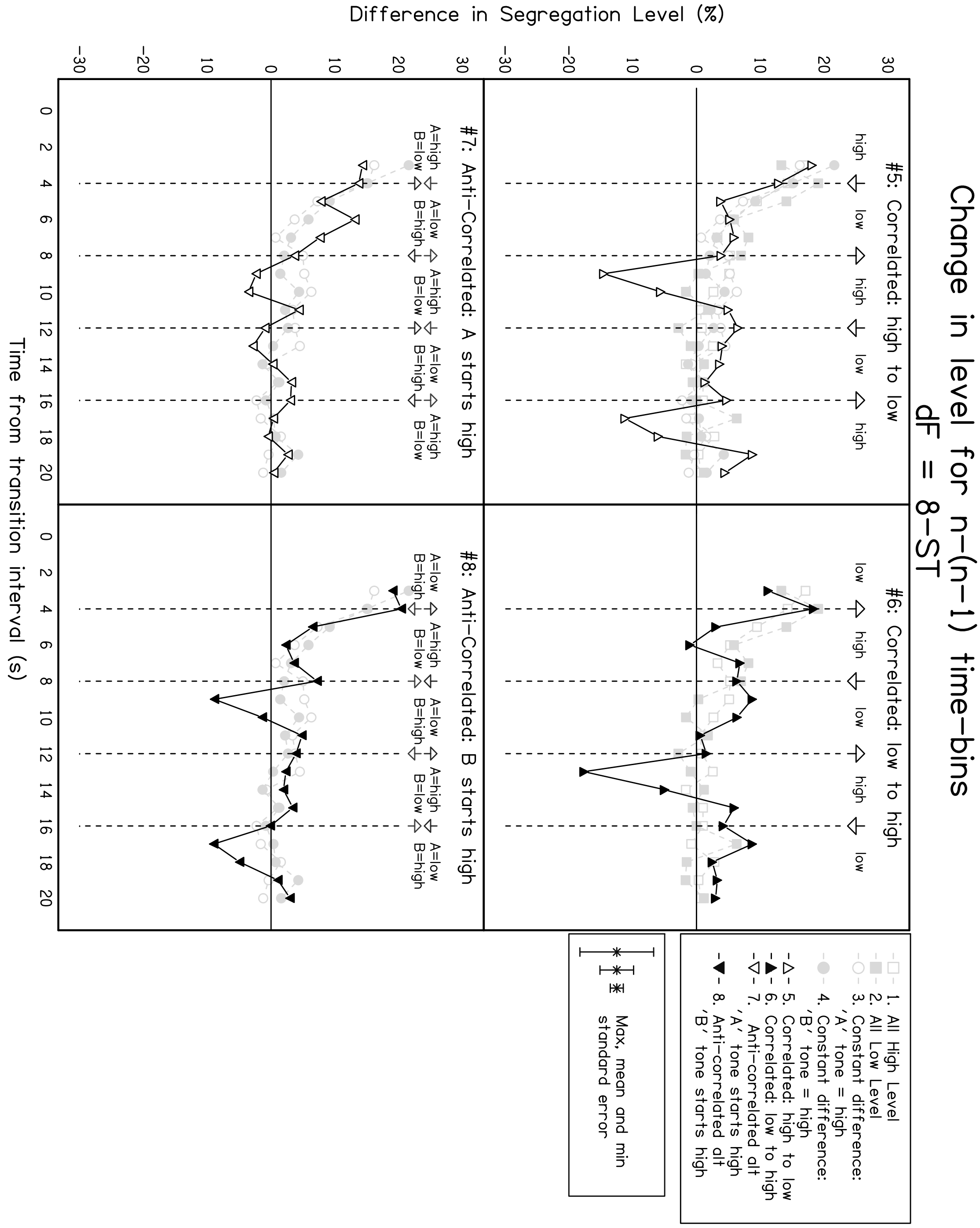

FIGURE 5.7: Results from Experiment 5 derived from the difference calculations for a Δf_{AB} of 8 ST. This was obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the the corresponding time-bin (n).The insert identifies the test conditions and the 3 error bars show the maximum, mean and minimum standard error across condition.

Table 5.7: Three-way repeated measures ANOVA, t=0 vs t=1 for Correlated Change Conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	1.321	0.287	0.107
Direction (A↑B↑ vs A↓B↓)	**(1,11)**	**5.749**	**0.035**	**0.343**
Transition Number	(3,33)	1.352	0.274	0.109
Δf_{AB} × Direction	(2,22)	2.573	0.099	0.190
Δf_{AB} × Transition Number	(6,66)	2.232	0.051	0.169
Direction × Transition Number	(3,33)	2.773	0.057	0.201
Δf_{AB} × Direction × Transition Number	(6,66)	0.631	0.705	0.054

Table 5.8: Three-way repeated measures ANOVA, t=0 vs t=1 for Anti-correlated Change Conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	1.115	0.346	0.330
Direction (A↑B↓ vs A↓B↑)	(1,11)	0.851	0.376	0.671
Transition Number	(3,33)	2.590	0.069	0.311
Δf_{AB} × **Direction**	**(2,22)**	**3.475**	**0.049**	**0.472**
Δf_{AB} × Transition Number	(6,66)	1.425	0.218	0.076
Direction × Transition Number	(3,33)	2.292	0.096	0.626
Δf_{AB} × Direction × Transition Number	(6,66)	1.012	0.425	0.642

Table 5.9: Three-way repeated measures ANOVA, average (t=-1, t=0) vs average (t=1, t=2) for Correlated Change Conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	2.189	0.136	0.166
Direction (A↑B↑ vs A↓B↓)	(1,11)	2.549	0.139	0.188
Transition Number	(3,33)	0.746	0.532	0.064
Δf_{AB} × Direction	(2,22)	0.561	0.579	0.048
Δf_{AB} × **Transition Number**	**(6,66)**	**3.396**	**0.006**	**0.236**
Direction × Transition Number	**(3,33)**	**4.466**	**0.010**	**0.289**
Δf_{AB} × Direction × Transition Number	(6,66)	1.307	0.267	0.106

Table 5.10: Three-way repeated measures ANOVA, average (t=-1, t=0) vs average (t=1, t=2)for Anti-correlated Change Conditions

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	2.370	0.117	0.177
Direction (A↑B↓ vs A↓B↑)	(1,11)	0.906	0.362	0.076
Transition Number	(3,33)	2.774	0.057	0.201
Δf_{AB} × **Direction**	**(2,22)**	**4.411**	**0.024**	**0.286**
Δf_{AB} × Transition Number	(6,66)	1.377	0.237	0.111
Direction × Transition Number	(3,33)	1.311	0.287	0.106
Δf_{AB} × Direction × Transition Number	(6,66)	0.762	0.603	0.065

TABLE 5.11: Pairwise Comparisons, t=0 vs t=1 (p-values shown in black, mean difference scores in grey.)

	Direction of Level Change			
	A↑B↑	A↓B↓	A↓B↑	A↑B↓
4 ST	**0.035**	0.281	0.056	0.677
	-9.7	-3.1	-12.7	1.0
6 ST	**0.018**	0.334	0.067	0.13
	-1.7	-2.9	-10.4	-7.5
8 ST	**0.006**	0.624	0.091	0.11
	-17.2	-1.1	-8.2	-6.0

TABLE 5.12: Pairwise Comparisons, average (t=-1, t=0) vs average (t=1, t=2) (p-values shown in black, mean difference scores in grey.)

	Direction of Level Change			
	A↑B↑	A↓B↓	A↓B↑	A↑B↓
4 ST	**0.052**	0.550	**0.031**	0.404
	-12.7	-3.6	**-20.9**	4.2
6 ST	**0.025**	0.309	**0.046**	0.176
	-23.3	-5.7	**-15.3**	-10.3
8 ST	**0.011**	0.270	0.057	0.055
	-21.4	-5.7	-12.6	-11.8

5.3.2.1 Effect of correlated level changes on the rate of build-up and resetting

As for Experiment 4 (Section 4.3), an abrupt correlated rise in level resulted in a negative peak within 1 s of the transition that was significant for all Δf_{AB}s (mean difference scores = -1.7 to -17.2 percentage points, $p < 0.05$, Table 5.11) whereas there was no discernible effect of correlated falls ($p > 0.05$, Table 5.11). Hence, there was a significant main effect of direction ($p = 0.035$, Table 5.7).

When the analysis window was extended to 2 s (Table 5.12), the influence of Δf_{AB} could be observed as the rise in level did not quite result in a significant resetting at 4 ST (mean difference score = -12.7 percentage points) but was more pronounced at 6 and 8 ST (mean difference scores = -23.3 and -21.4 percentage points, $p < 0.05$, Table 5.12). This was a result of the continued increase in the rate of loss of segregation 2 s after the transitions, as the difference scores remained negative in this interval for both the 6- and 8-ST conditions. Including the second interval within the analysis also revealed significant interactions between Δf_{AB} × Transition Number, and Direction × Transition Number ($p = 0.006$ and $p = 0.010$, Table 5.9); these interactions narrowly missed significance in the first epoch analysis.

5.3.2.2 Effect of anti-correlated level changes on the rate of build-up and resetting

The first epoch analysis for the anti-correlated changes did not demonstrate clear effects of these transitions, as no individual cases were significant. However, there was evidence of a trend towards a significant effect of rises of the 'B' tones ($p < 0.1$ in all cases, Table 5.11). Whilst there was a marginally significant interaction between Δf_{AB} and Direction resulting from the reduced resetting effect of 'B'-tone rises ($p = 0.049$, Table 5.8), no other interaction terms were significant in the first epoch analysis.

Given that, for anti-correlated level changes, the 'B'-tone rises caused more sustained resetting, the second epoch analysis revealed significant falls in segregation level for the 4-ST (mean difference=-20.9 percentage points, $p = 0.031$, Table 5.12) and 6-ST cases (mean difference= -15.3 percentage points, $p = 0.046$, Table 5.12); the fall for the 8-ST case was smaller (-12.1 percentage points) and was not quite significant. The decreasing effect of the 'B'-tone rises as Δf_{AB} was increased is reflected in the more significant Δf_{AB} × Direction interaction ($p = 0.024$, Table 5.10).

To sum up, sudden correlated rises in level for 'A' and 'B' tones typically produce rapid falls in stream segregation, whereas correlated falls in level have little or no effect. The persistence of the response to anti-correlated changes tends to be longer. A↓B↑ transitions usually increase subsequent resetting, but A↑B↓ transitions do not usually produce reliable increases in segregation (overshoot). The effects of correlated and anti-correlated changes also show different dependencies on Δf_{AB}.

5.3.3 Discussion

Consistent with earlier findings (Van Noorden, 1975), a constant level difference between the 'A' and 'B' subsets resulted in an elevated rate of build-up and higher overall level of segregation than when both subsets were presented at the same level, suggesting that the level difference between subsets of tones may cue separate perceptual objects. This influence evidently weakened at greater frequency separations, as the effect of frequency separation became increasingly dominant.

As seen in Experiment 4, the correlated alternating cases initially showed similar patterns of build-up to the constant-same cases across frequency separations; this build-up was partially reset subsequent to rising transitions. Falls in level had little effect (cf. Rogers and Bregman, 1998). The resetting effect of correlated changes could be observed to increase with frequency separation. This could be due to the increased scope for resetting available as a result of the faster rate of build-up at greater frequency separations.

In the case of the anti-correlated alternating conditions, the pattern of build-up was less consistent across frequency separations. At the lower frequency separation of 4 ST, a distinct resetting was observed following the A↓B↑ transitions. If, as for the correlated changes, a rise in level causes resetting, this would indicate that the 'B'-tone transition had a stronger influence than that of the 'A' tone (causing a stronger drop in segregation when it changes from high to low than any increase in segregation resulting from the opposing 'A'-tone change) . Additionally for the 4-ST case, the B↓ transition could be observed to result in a rapid rise in segregation level or 'overshoot' (cf. tone-to-dyad transitions in Experiment 2). This pattern of resetting and overshoot was reduced but still visible for the 6-ST case, but any effect of the anti-correlated changes was essentially absent for the 8-ST case.

In accordance with the hypotheses stated earlier, the anti-correlated transitions would have been expected to cause 'overshoot' in response to all transitions if resetting was a consequence of correlated changes in both tone subsets. As is evident from the results here, this source grouping argument cannot explain the patterns of resetting and overshoot observed, both of which may occur in response to anti-correlated changes. A more plausible explanation would be that resetting and overshoot are consequences of neural adaptation, with the two tone subsets exerting an asymmetrical influence on the overall percept.

A key question that remains is which aspect of the two tone subsets (higher vs. lower tone frequency, or higher vs. lower tone density) are responsible for the resetting and overshoot evident in response to anti-correlated changes. This issue is explored in Experiment 6.

5.4 Experiment 6: The Effect of Triplet Structure on Anti-Correlated Level Changes

Experiment 6 followed on from Experiment 5 by exploring whether the directional effects on stream segregation of specific transitions in the 'A' and 'B' subsets (A↑B↓ or A↓B↑) arose from their frequencies or from their within-triplet positions. This was done using anti-correlated level changes in the context of 'LHL-' and 'HLH-' triplets, where 'L' refers to the lower frequency tone and 'H' refers to the higher frequency tone. The different sound intensities are referred to as either 'low' or 'high' level (words written in full to distinguish level changes from frequency differences). For both stimulus configurations, the effects of sudden transitions in level were compared with those of constant difference.

5.4.1 Method

The method and procedure was as for Experiment 3, using continuous assessment of 20-s 'ABA-'sequences. The conditions below were presented at Δf_{AB} values of 4, 6, and 8 ST. As for Experiment 5, the low-level sounds were set to 3 dB below the baseline and high-level sounds were set to 3 dB above, so the output ranged between 67 and 73

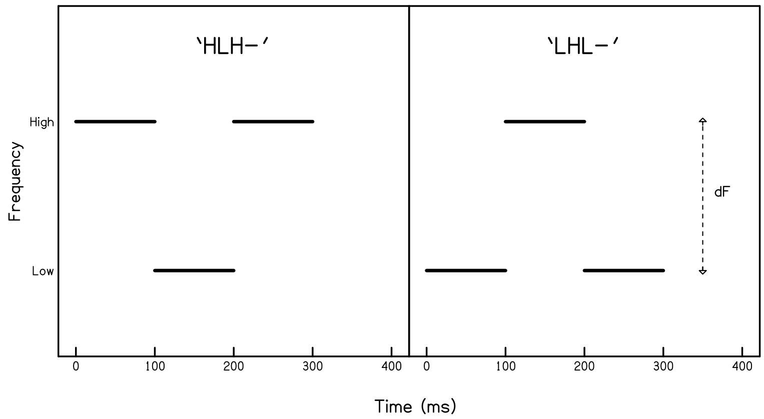

FIGURE 5.8: Illustration of the HLH- and LHL- triplet structures used in Experiment 6.

dB SPL.The stimulus configurations for these conditions are summarised in Figure 5.9. The 'L' tone was constant at 1 kHz for both 'LHL-' and 'HLH-' triplet configurations.

5.4.2 Conditions

1. *All mid-level* (70 dB SPL)
2. *Constant difference 'A' = high & 'B' = low* (6 dB difference)
3. *Constant difference 'A' = low & 'B' = high* (6 dB difference)
4. *Alternating –'A' high first:* 'A' and 'B' tones switch level every 4 s, high → low (& v/v). Initially 'A' = high & 'B' = low.
5. *Alternating –'B' high first:* As for condition 4, but initially 'A' = low & 'B' = high.

Conditions 1-5: $A_f < B_f$, i.e. 'LHL-'triplet structure (as for Experiment 5).

Conditions 6-10: $A_f > B_f$, i.e. 'HLH-'triplet structure.

It was hypothesised that 'HLH-' sequences would generally be perceived similarly to 'LHL-' sequences, although there may be a slight increase in segregation owing to increased presentation of the 'H' tone, resulting in a higher weighted-average frequency for the sequence as a whole. If the within-triplet structure was the key determinant of the effects of anti-correlated changes on streaming observed in Experiment 5, then it would be anticipated that 'B'-tone rises would cause resetting, and 'B'-tone falls would result in overshoot. Alternatively, if the base frequency of the tone determined the effect then it might be expected that either the 'L' or 'H' tone

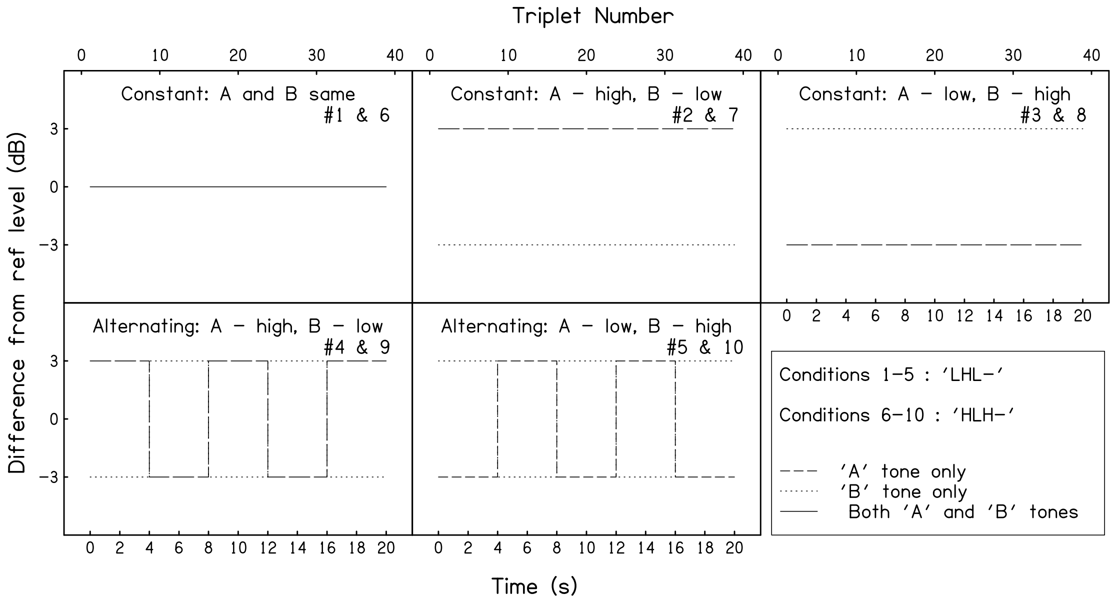

FIGURE 5.9: Illustration of the conditions in Experiment 6.

would consistently cause resetting following a rise in level, or overshoot following a fall in level.

5.4.3 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. All conditions were presented during each of the 10 blocks over two sessions.

5.4.4 Results

The responses were analysed using the same approach as for Experiment 5. This time five three-way repeated measures ANOVAs were conducted; the first compared the absolute effect of triplet structure using the 'HLH-' and 'LHL-' constant cases (Table 5.13). The rest of the ANOVAs considered the two triplet configurations separately to avoid the need for 4-way analyses. The second (Table 5.14) and third (Table 5.16) included the constant-same and constant-difference cases for the 'LHL-' and 'HLH-' configurations, respectively (top right-hand panel of Figures 5.10-5.12). The fourth (Table 5.18) and fifth (Table 5.19) compared the alternating and constant-difference cases for the 'LHL-' and 'HLH-' configurations, respectively. As expected, most of these

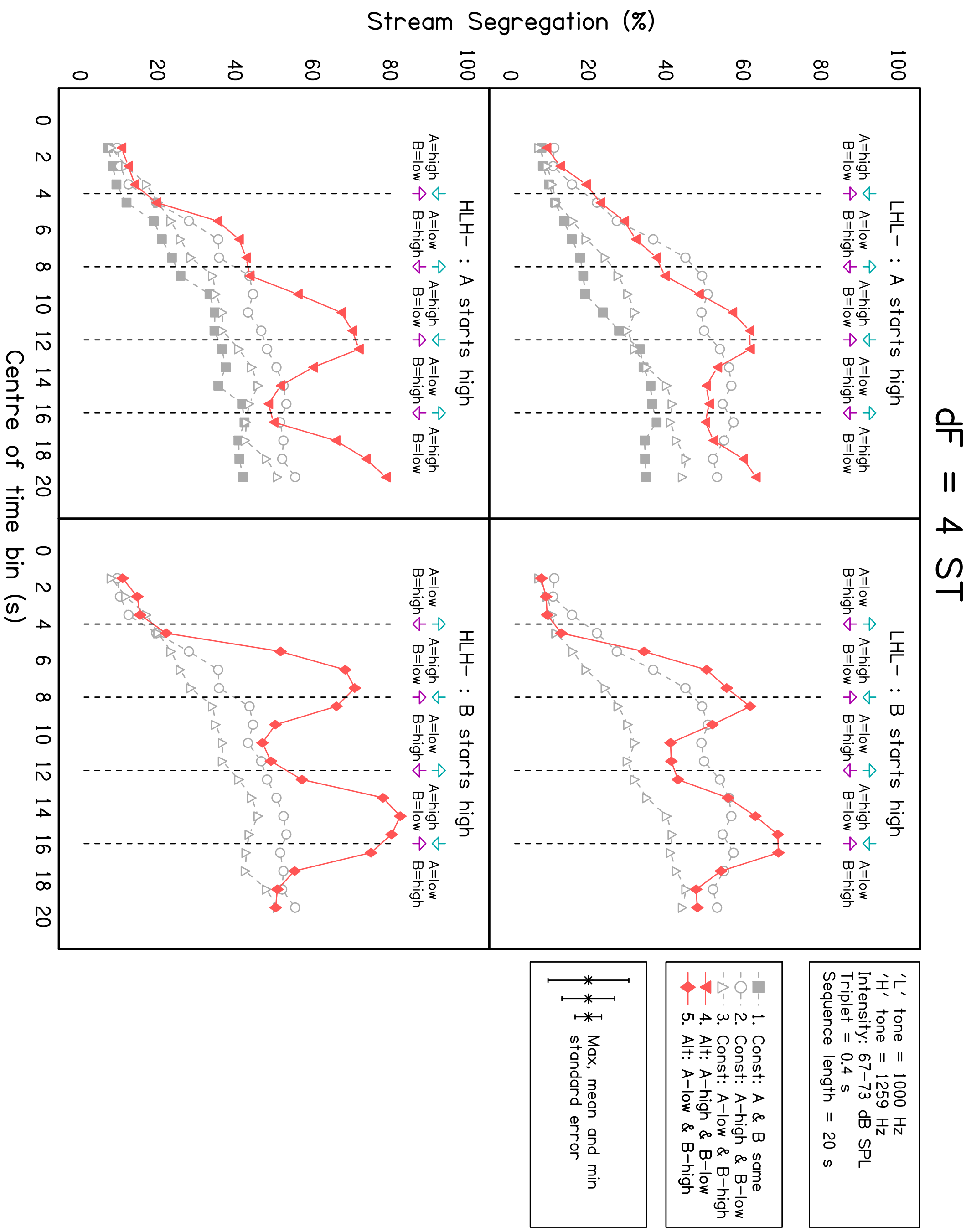

Figure 5.10: The stream segregation data averaged across listeners from Experiment 6, displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

ANOVAs (all but the fourth) showed significant main effects of Δf_{AB} and Time Interval ($p < 0.001$).

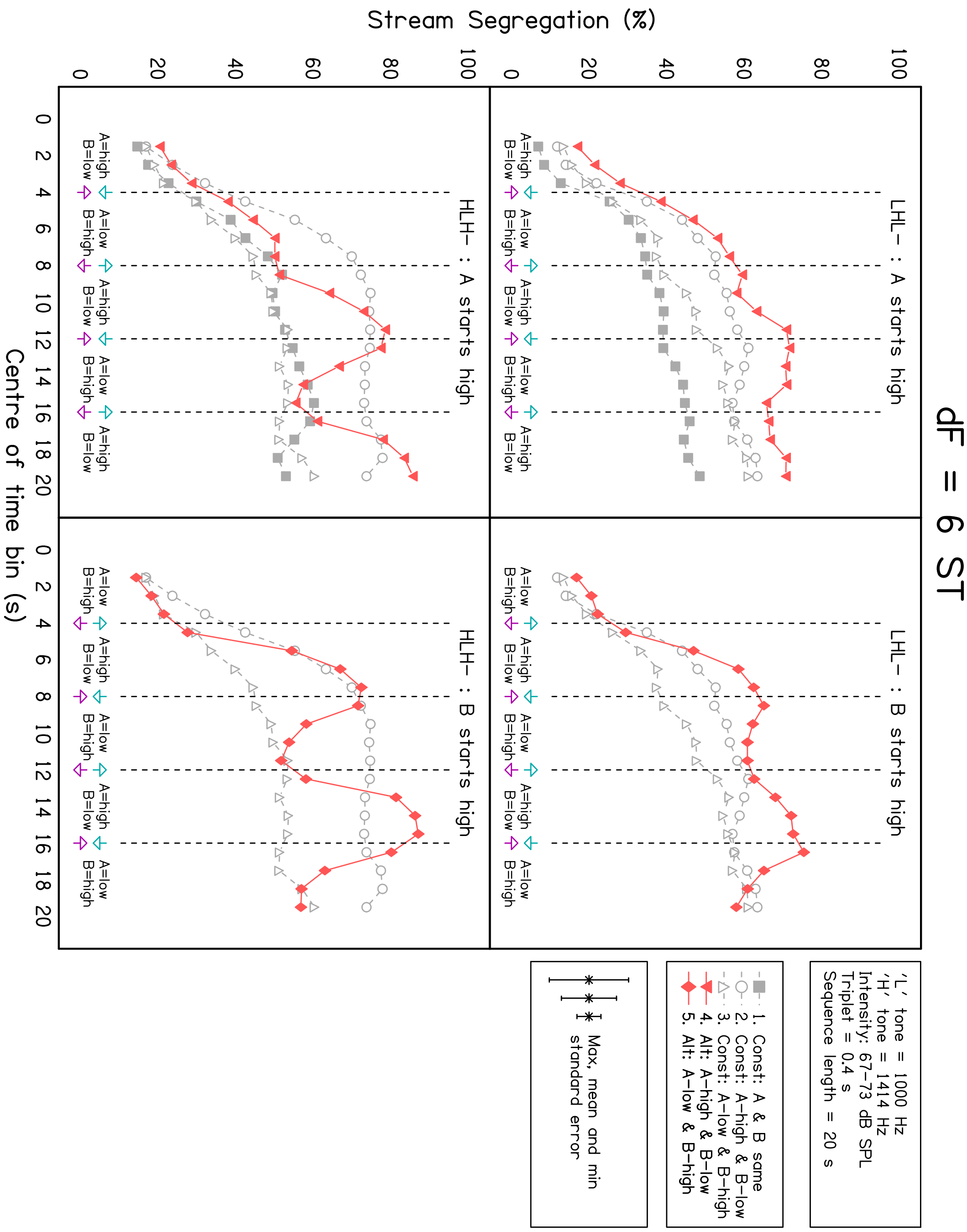

Figure 5.11: The stream segregation data averaged across listeners from Experiment 6, displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

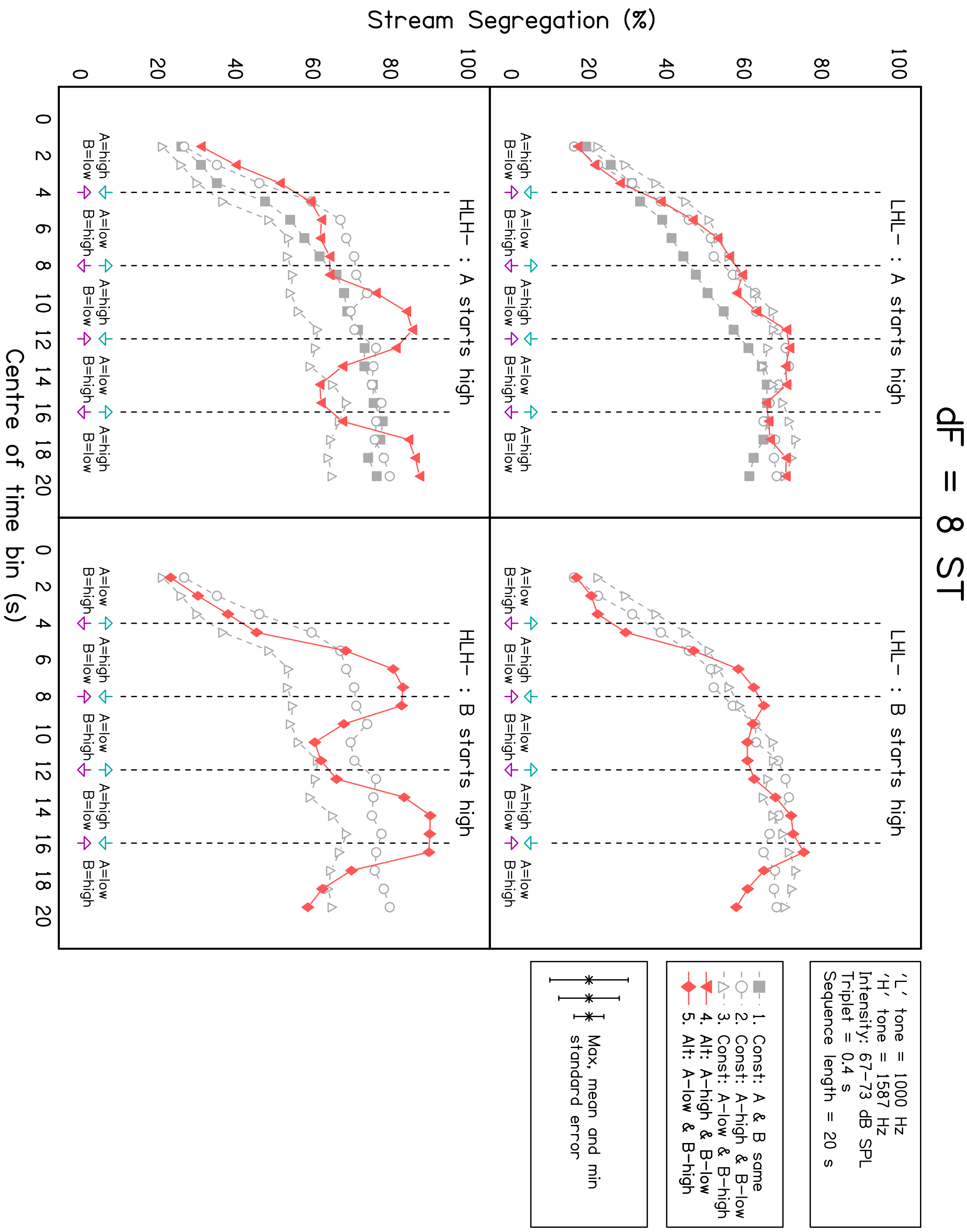

FIGURE 5.12: The stream segregation data averaged across listeners from Experiment 6, displaying the pattern of build-up over the 20-s test sequence for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

Table 5.13: Three-way repeated measures ANOVA comparing LHL- and HLH-constant conditions (A & B = same level.)

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**13.172**	**<0.001**	**0.545**
Condition	(1,11)	2.858	0.119	0.206
Time Interval	**(18,198)**	**17.741**	**<0.001**	**0.617**
Δf_{AB} × Condition	(2,22)	1.407	0.266	0.113
Δf_{AB} × **Time Interval**	**(36,396)**	**1.623**	**0.015**	**0.129**
Condition × Time Interval	(18,198)	0.595	0.900	0.051
Δf_{AB} × Condition × Time Interval	(36,396)	0.617	0.961	0.053

Table 5.14: Three-way repeated measures ANOVA comparing LHL- constant conditions (A & B same, and both A & B constant difference conditions.)

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**8.683**	**0.002**	**0.4**
Condition	**(1,11)**	**5.24**	**0.014**	**0.323**
Time Interval	**(18,198)**	**15.79**	**<0.001**	**0.589**
Δf_{AB} × **Condition**	**(2,22)**	**3.552**	**0.014**	**0.244**
Δf_{AB} × Time Interval	(36,396)	1.406	0.065	0.113
Condition × Time Interval	**(18,198)**	**2.202**	**<0.001**	**0.167**
Δf_{AB} × Condition × Time Interval	(36,396)	0.739	0.947	0.063

Table 5.15: Pairwise Comparison of Conditions for LHL- constant conditions (A & B same, and both A & B constant difference conditions.)

[I] Condition	[J] Condition	Mean Difference [I-J] (%)	Std. Error (%)	*p*
All reference level	**Constant Diff (A-high, B-low)**	**-12.7**	**4.1**	**0.010**
	Constant Diff (A-low, B-high)	**-7.0**	**2.3**	**0.011**
Constant Diff (A-high, B-low)	**All reference level**	**12.7**	**4.1**	**0.010**
	Constant Diff (A-low, B-high)	5.7	5.0	0.274
Constant Diff (A-low, B-high)	**All reference level**	**7.0**	**2.3**	**0.011**
	Constant Diff (A-high, B-low)	-5.7	5.0	0.274

TABLE 5.16: Three-way repeated measures ANOVA comparing HLH- constant conditions (A & B same, and both A & B constant difference conditions.)

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**14.219**	**<0.001**	**0.564**
Condition	**(2,22)**	**11.765**	**<0.001**	**0.517**
Time Interval	**(18,198)**	**15.045**	**<0.001**	**0.578**
Δf_{AB} × Condition	**(4,44)**	**2.765**	**0.039**	**0.201**
Δf_{AB} × Time Interval	(36,396)	1.374	0.078	0.111
Condition × Time Interval	(36,396)	1.333	0.100	0.108
Δf_{AB} × Condition × Time Interval	(72,792)	1.022	0.432	0.085

TABLE 5.17: Pairwise Comparison of Conditions for HLH- constant conditions (A & B same, and both A & B constant difference conditions.)

[I] Condition	[J] Condition	Mean Difference [I-J] (%)	Std. Error (%)	*p*
All reference level	**Constant Diff (A-high, B-low)**	**-10.7**	**2.8**	**0.003**
	Constant Diff (A-low, B-high)	-2.2	2.6	0.417
Constant Diff (A-high, B-low)	**All reference level**	**10.7**	**2.8**	**0.003**
	Constant Diff (A-low, B-high)	**13.0**	**3.2**	**0.002**
Constant Diff (A-low, B-high)	All reference level	2.2	2.6	0.417
	Constant Diff (A-high, B-low)	**-13.0**	**3.2**	**0.002**

TABLE 5.18: Three-way repeated measures ANOVA comparing LHL- constant A & B different and alternating conditions.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**8.838**	**0.002**	**0.445**
Condition	(3,33)	1.069	0.375	0.089
Time Interval	**(18,198)**	**23.661**	**<0.001**	**0.683**
Δf_{AB} × **Condition**	**(6,66)**	**2.909**	**0.014**	**0.209**
Δf_{AB} × Time Interval	(36,396)	0.768	0.832	0.065
Condition × Time Interval	**(54,594)**	**1.552**	**0.009**	**0.124**
Δf_{AB} × Condition × Time Interval	(108,1188)	1.224	0.067	0.100

TABLE 5.19: Three-way repeated measures ANOVA comparing HLH- constant A & B different and alternating conditions.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**9.372**	**0.001**	**0.460**
Condition	**(3,33)**	**3.368**	**0.023**	**0.249**
Time Interval	**(18,198)**	**24.083**	**<0.001**	**0.686**
Δf_{AB} × **Condition**	**(6,66)**	**2.794**	**0.018**	**0.203**
Δf_{AB} × **Time Interval**	**(36,396)**	**2.076**	**<0.001**	**0.159**
Condition × Time Interval	**(54,594)**	**5.517**	**<0.001**	**0.334**
Δf_{AB} × Condition × Time Interval	(108,1188)	1.058	0.331	0.088

TABLE 5.20: Pairwise Comparison of Conditions for HLH- constant A & B different and alternating conditions. (Constant Diff 1 = A high, B low. Constant Diff 2 = A low, B high. Alternating 1 = A high first. Alternating 2 = B high first.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	*p*
Constant Diff (1)	**Constant Diff (2)**	**12.9**	**3.2**	**0.002**
	Alternating (1)	-1.1	6.1	0.855
	Alternating (2)	-2.0	6.4	0.762
Constant Diff (2)	**Constant Diff (1)**	**-12.9**	**3.2**	**0.002**
	Alternating (1)	**-14.0**	**5.7**	**0.032**
	Alternating (2)	**-14.9**	**6.2**	**0.036**
Alternating (1)	Constant Diff (1)	1.1	6.1	0.855
	Constant Diff (2)	**14.0**	**5.7**	**0.032**
	Alternating (2)	-0.9	1.7	0.620
Alternating (2)	Constant Diff (1)	2.0	6.4	0.762
	Constant Diff (2)	**14.9**	**6.2**	**0.036**
	Alternating (1)	0.9	1.7	0.620

5.4.5 Overall effect of triplet structure

Comparison of the two constant 'A' and 'B' same cases in the first analysis revealed no significant effect of triplet structure ('LHL-' vs. 'HLH-') on the overall extent of segregation perceived. Regardless of triplet structure, both conditions produced the expected pattern of build-up, which was enhanced at larger Δf_{ABs}. Accordingly, whilst Δf_{AB}, Time interval and the interaction between Δf_{AB} and Time Interval were significant ($p < 0.05$), Condition produced no significant main effect ($p = 0.119$, Table 5.13), or interaction terms involving Condition ($p > 0.05$, Table 5.13).

5.4.5.1 Triplet structure and a constant level difference between tone subsets

When presented within the 'LHL-' triplet structure, the constant all-same case produced significantly less segregation than the constant 'A' & 'B' difference conditions, indicated by the significant main effect of Condition ($p = 0.014$, Table 5.14). Both versions of the constant-difference conditions (A-high, B-low and A-low, B-high) were perceived as significantly more segregated than the constant-same reference case (mean difference = 7.0-12.7 percentage points, $p < 0.05$, Table 5.15), but were not significantly different from one another ($p = 0.274$, Table 5.15). The higher rate of build-up for the constant difference cases accounts for the significant interaction term between Condition and Time Interval ($p < 0.001$, Table 5.14). At higher Δf_{ABs} ceiling effects limited the differences between all constant cases (see top-right panel, Figure 5.12), shown in the significant two-way interaction term for Δf_{AB} and Condition ($p = 0.014$, Table 5.15).

For sequences presented within the 'HLH-' triplet structure, only the constant-difference (A-high, B-low) condition tended to induce significantly more segregation than either of the other conditions (mean difference = 2.8-3.2 percentage points, $p < 0.05$, Table 5.17) also shown in the main effect of Condition ($p < 0.001$, Table 5.16). This difference between the A-high and A-low cases was lessened as Δf_{AB} rose, leading to a significant interaction between Δf_{AB} and Condition ($p = 0.039$, Table 5.16). The anticipated elevation of the rate of build up as Δf_{AB} was increased did not produce a significant interaction term between Δf_{AB} and Time Interval. This may be because whilst the constant-difference (A-high, B-low) appears to increase with Δf_{AB}

(bottom left-hand panel of Figures 5.10-5.12) both the constant-difference (A-high, B-low) and constant 'A' and 'B' same conditions tended not to exceed the 60% extent of segregation across Δf_{AB}.

5.4.5.2 Triplet structure and anti-correlated level changes

Anti-correlated changes within 'LHL-' sequences could be observed to produce resetting at transitions A↓B↑ (both top panels of Figures 5.10-5.12), but the initial analysis of constant and alternating cases did not show a significant main effect of Condition (p = 0.375, Table 5.18). This outcome could be a result of weakening resetting in response to abrupt changes occurring within 'LHL-' sequences as Δf_{AB} was increased, evident in comparison of Figures 5.10-5.12. This suppression of resetting at higher Δf_{ABs} is shown in the significant interaction between Δf_{AB} and Condition (p = 0.014, Table 5.18). The transient nature of the resetting following an abrupt change was reflected in the significant Condition × Time Interval interaction (p = 0.009, Table 5.18).

The A↓B↑ transitions occurring within anti-correlated, alternating level sequences in the 'HLH-' configuration also produced resetting. Unlike for the 'LHL-' cases, here 'overshoot' was also visible following A↑B↓ across all Δf_{ABs} (see the two lower panels of Figures 5.10-5.12). Comparison of the constant-difference and anti-correlated alternating 'HLH-' conditions did show a significant main effect of Condition (p = 0.023, Table 5.19), because of the substantial 'resetting' in response to A↓B↑ and 'overshoot' following A↑B↓. Only the constant difference (A-low, B-high) case was significantly lower than the other constant difference (A-high, B-low) and both anti-correlated, alternating cases (mean difference = 12.9-14.9 percentage points, p < 0.05, Table A.21). Again, this is most likely accounted for by the transient nature of both overshoot and resetting, also reflected in the significant Condition × Time Interval interaction (p < 0.001, Table 5.19). Visible in the patterns of segregation extent over time for the anti-correlated 'HLH-' alternations, (see the two lower panels of Figures 5.10-5.12) is that the profiles for both alternating cases remains similar across Δf_{AB} unlike the constant-difference cases which increase in the overall extent of segregation. This is also shown in the significant interaction term between Δf_{AB} and Condition (p = 0.039, Table 5.19).

5.4.6 The effect of rate of change on the extent of segregation

As for Experiment 5, the transient effects of the anti-correlated level changes in the two alternating conditions were explored further using the same method. Again, for each of the two triplet structures, the transitions were grouped so that the A↓B↑ transitions could be considered together, and the A↑B↓ transitions could also be grouped together. This provided the facility to investigate the influence of different transitions and triplet structures using four ANOVAs. The first and second separated the data on the analysed the transitions for (‘LHL-’ and ‘HLH-’structures, respectively. This permitted comparison of the effects of A↓B↑ and A↑B↓ transitions within each triplet configuration. The third and fourth separated the data on the basis of transition direction (A↓B↑ and A↑B↓) so that the extent of any effect caused by these transitions could be compared for each triplet structure ‘LHL-’and ‘HLH-’ structures could be compared.

Figures 5.13-5.15 summarise these data plotted over the 20-s sequence duration for each Δf_{AB}. As previously, the data was then analysed twice: the first-epoch set of three-way repeated measures ANOVAs were run on 1-s intervals pre- and post-transition (see Tables 5.21, 5.22, 5.23 and 5.24) and the second-epoch set were extended to include 2-s pre and post transition (Tables 5.27, 5.28, 5.29 and 5.30).

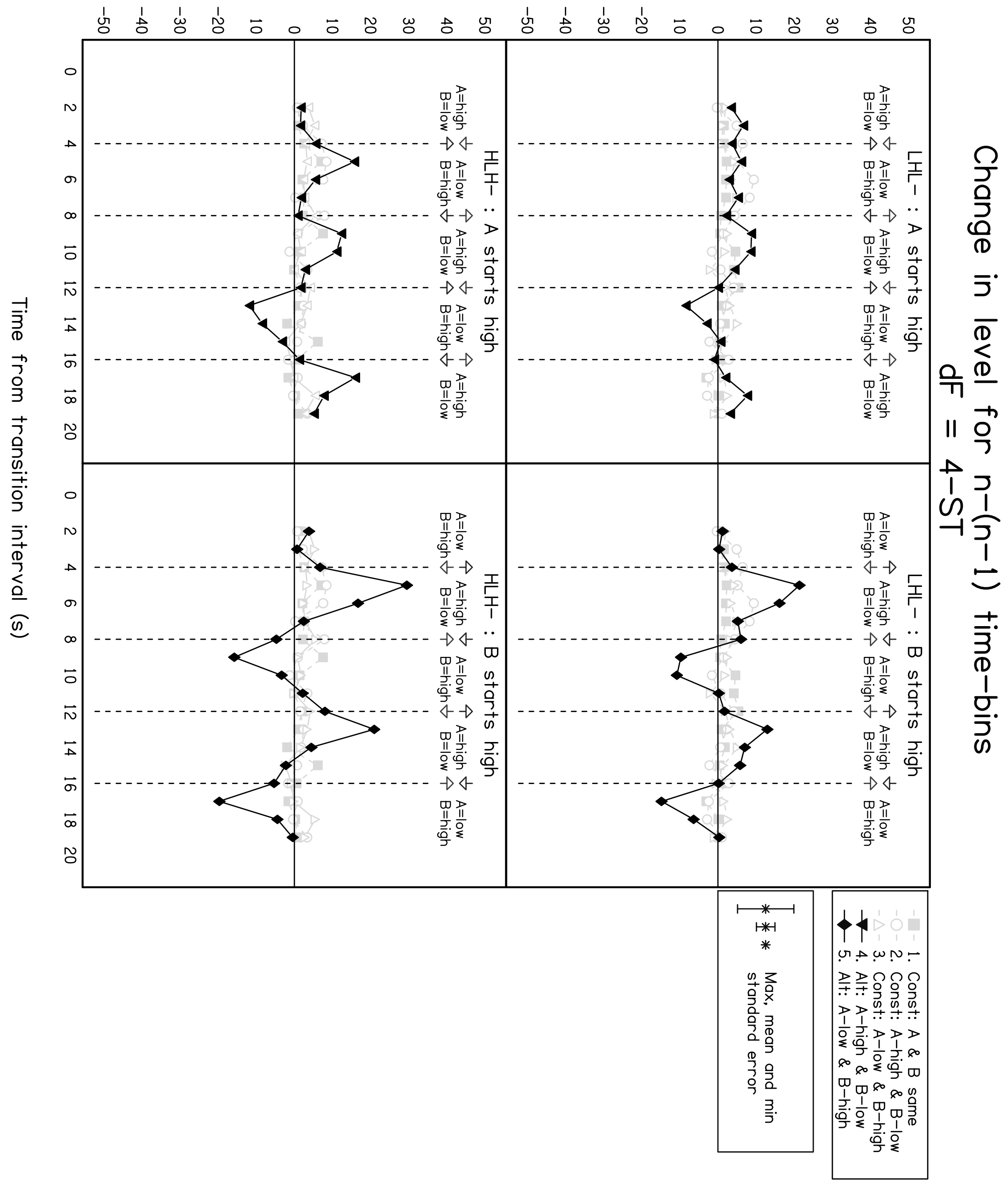

Figure 5.13: Results for Δf_{AB} = 4 ST in Experiment 6. These values were derived from the difference calculations, obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the corresponding time-bin (n).

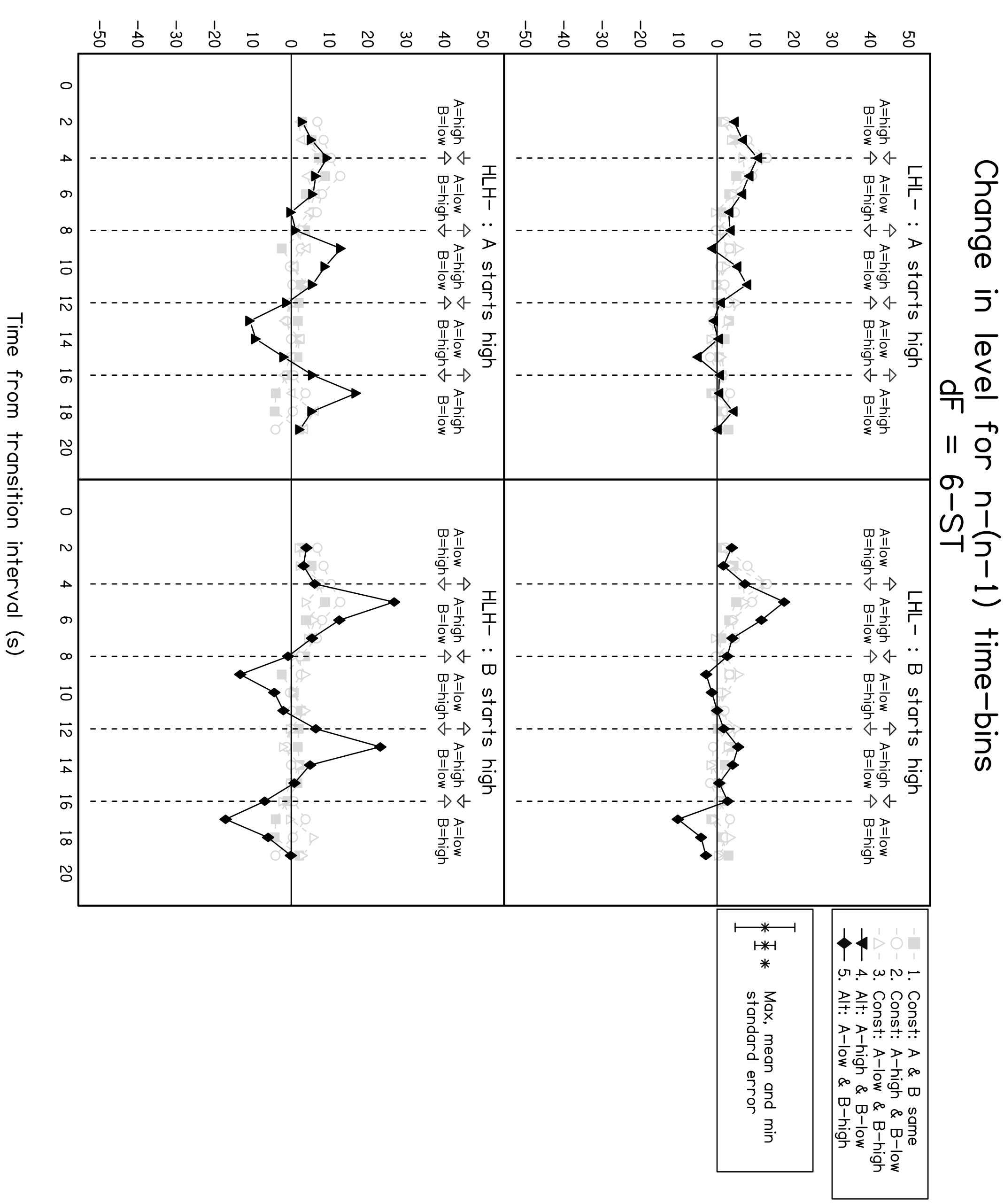

FIGURE 5.14: Results for Δf_{AB} = 6 ST in Experiment 6. These values were derived from the difference calculations, obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the corresponding time-bin (n).

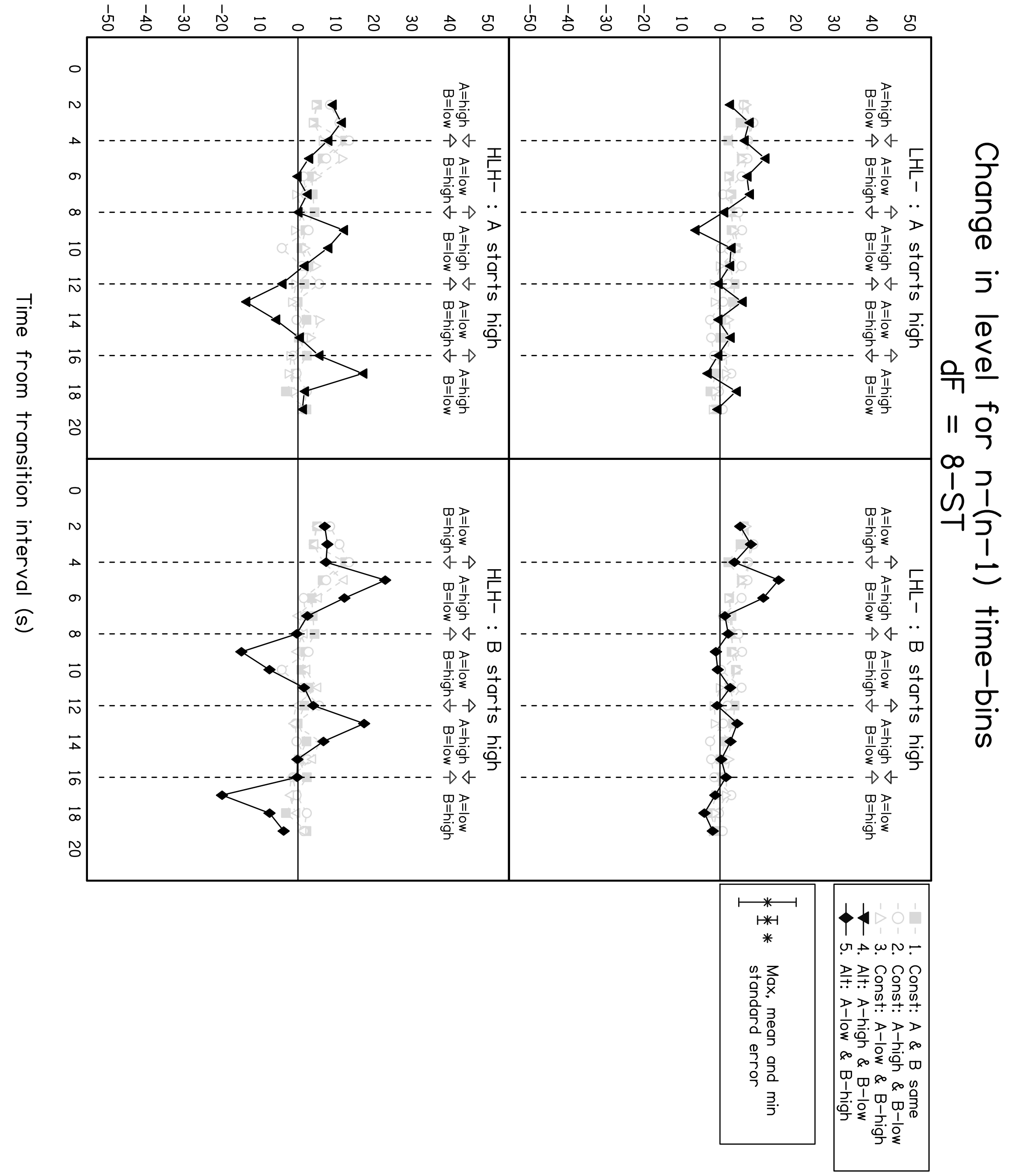

Figure 5.15: Results for Δf_{AB} = 8 ST in Experiment 6. These values were derived from the difference calculations, obtained by calculating the difference in segregation level between the current and previous time-bins for each time-bin (n-[n-1], where n=current time-bin) and plotting the value for the corresponding time-bin (n).

TABLE 5.21: Three-way repeated measures ANOVA, t=0 vs t=1 for LHL Triplet Structure.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	0.404	0.673	0.035
Direction (A↓B↑ vs A↑B↓)	(1,11)	0.82	0.385	0.069
Transition Number	**(3,33)**	**5.849**	**0.003**	**0.347**
Δf_{AB} × **Direction**	**(2,22)**	**6.505**	**0.006**	**0.372**
Δf_{AB} × Transition Number	(6,66)	0.803	0.571	0.068
Direction × Transition Number	(3,33)	1.18	0.332	0.097
Δf_{AB} × Direction × Transition Number	(6,66)	0.404	0.673	0.035

TABLE 5.22: Three-way repeated measures ANOVA, t=0 vs t=1 for HLH Triplet Structure.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**4.058**	**0.033**	**0.269**
Direction (A↓B↑ vs A↑B↓)	**(1,11)**	**8.471**	**0.014**	**0.435**
Transition Number	**(3,33)**	**4.162**	**0.013**	**0.274**
Δf_{AB} × Direction	(2,22)	0.067	0.935	0.006
Δf_{AB} × Transition Number	(6,66)	1.436	0.214	0.115
Direction × Transition Number	(3,33)	2.504	0.076	0.185
Δf_{AB} × Direction × Transition Number	(6,66)	2.184	0.055	0.166

TABLE 5.23: Three-way repeated measures ANOVA, t=0 vs t=1 for A↓B↑.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	0.374	0.692	0.033
Triplet Structure (LHL- vs HLH-)	(1,11)	1.151	0.306	0.095
Transition Number	**(3,33)**	**4.346**	**0.011**	**0.283**
Δf_{AB} × **Triplet Structure**	**(2,22)**	**3.630**	**0.043**	**0.248**
Δf_{AB} × Transition Number	(6,66)	2.182	0.056	0.166
Triplet Structure × Transition Number	(3,33)	0.299	0.826	0.026
Δf_{AB} × Triplet Structure × Transition Number	(6,66)	0.439	0.850	0.038

TABLE 5.24: Three-way repeated measures ANOVA, t=0 vs t=1 for A↑B↓.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	3.022	0.069	0.215
Triplet Structure (LHL- vs HLH-)	(1,11)	4.591	0.055	0.294
Transition Number	**(3,33)**	**6.957**	**0.001**	**0.387**
Δf_{AB} × Triplet Structure	(2,22)	0.089	0.915	0.008
Δf_{AB} × Transition Number	(6,66)	1.755	0.122	0.138
Triplet Structure × Transition Number	**(3,33)**	**4.282**	**0.012**	**0.280**
Δf_{AB} × Triplet Structure × Transition Number	(6,66)	1.124	0.358	0.093

TABLE 5.25: Pairwise Comparisons, t=0 vs t=1 (p-values shown in black, mean difference scores in grey.)

	Direction of Level Change			
	LHL (A↓B↑)	LHL (A↑B↓)	HLH (A↓B↑)	HLH (A↑B↓)
4 ST	0.072	0.143	0.217	**0.007**
	-5.5	3.1	-4.9	**10.7**
6 ST	0.574	0.248	0.066	**0.002**
	-2.5	2.5	-6.3	**8.5**
8 ST	0.425	0.741	**0.038**	0.078
	1.9	-0.8	**-10.0**	6.5

TABLE 5.26: Pairwise Comparisons, average (t=-1, t=0) vs average (t=1, t=2) (p-values shown in black, mean difference scores [%] in grey.)

	Direction of Level Change			
	LHL (A↓B↑)	LHL (A↑B↓)	HLH (A↓B↑)	HLH (A↑B↓)
4 ST	**0.040**	**0.003**	0.165	**0.004**
	-9.6	**9.9**	-7.9	**19.7**
6 ST	0.631	0.087	**0.049**	**0.002**
	-2.9	6.5	**-10.4**	**21.5**
8 ST	0.516	0.705	**0.028**	**0.009**
	2.7	1.5	**-14.5**	**15.8**

Table 5.27: Three-way repeated measures ANOVA average (t=-1, t=0) vs average (t=1, t=2) for LHL Triplet Structure.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	0.840	0.445	0.071
Direction (A↓B↑ vs A↑B↓)	(1,11)	2.009	0.184	0.154
Transition Number	**(3,33)**	**3.645**	**0.022**	**0.249**
Δf_{AB} × **Direction**	**(2,22)**	**9.669**	**0.001**	**0.468**
Δf_{AB} × Transition Number	(6,66)	0.909	0.494	0.076
Direction × Transition Number	(3,33)	1.823	0.162	0.142
Δf_{AB} × Direction × Transition Number	(6,66)	0.280	0.944	0.025

Table 5.28: Three-way repeated measures ANOVA average (t=-1, t=0) vs average (t=1, t=2) for HLH Triplet Structure.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	(2,22)	2.167	0.138	0.165
Direction (A↓B↑ vs A↑B↓)	**(1,11)**	**9.049**	**0.012**	**0.451**
Transition Number	(3,33)	2.347	0.091	0.176
Δf_{AB} × **Direction**	**(2,22)**	**4.176**	**0.029**	**0.275**
Δf_{AB} × **Transition Number**	**(6,66)**	**2.472**	**0.032**	**0.183**
Direction × Transition Number	**(3,33)**	**7.343**	**0.001**	**0.400**
Δf_{AB} × **Direction × Transition Number**	**(6,66)**	**5.789**	**<0.001**	**0.345**

Table 5.29: Three-way repeated measures ANOVA, average (t=0, t=-1) vs average (t=2, t=1) for A↓B↑.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**8.182**	**0.002**	**0.427**
Triplet Structure (LHL- vs HLH-)	(1,11)	0.455	0.514	0.040
Transition Number	**(3,33)**	**3.343**	**0.031**	**0.233**
Δf_{AB} × Triplet Structure	(2,22)	2.140	0.142	0.163
Δf_{AB} × **Transition Number**	**(6,66)**	**6.610**	**<0.001**	**0.375**
Direction × Transition Number	(3,33)	0.657	0.584	0.056
Δf_{AB} × Triplet Structure × Transition Number	(6,66)	2.134	0.061	0.162

Table 5.30: Three-way repeated measures ANOVA average (t=0, t=-1) vs average (t=2, t=1) for A↑B↓.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**13.919**	**<0.001**	**0.559**
Triplet Structure (LHL- vs HLH-)	(1,11)	2.577	0.137	0.190
Transition Number	**(3,33)**	**5.154**	**0.005**	**0.319**
Δf_{AB} × Triplet Structure	(2,22)	0.131	0.878	0.012
Δf_{AB} × Transition Number	(6,66)	1.754	0.122	0.138
Direction × Transition Number	**(3,33)**	**6.556**	**0.001**	**0.373**
Δf_{AB} × Triplet Structure × Transition Number	(6,66)	2.150	0.059	0.163

5.4.6.1 Anti-correlated transitions

There was a clear asymmetry between the effects of A↓B↑ and A↑B↓ transitions on the perception of 'HLH-' sequences as shown by the significant effect of direction for the first epoch and second epoch ANOVAs, ($p = 0.014$, Table 5.22; $p = 0.012$, Table 5.28).

The A↓B↑ transition resulted in a negative peak in the difference plots that continued to increase over the 2-s post transition. This prolonged negative peak indicated an increasing rate of loss of segregation, as shown by the increasingly negative mean difference scores for the second epoch analysis (Table 5.26) in comparison with the first (Table 5.25). Also notable was the increasing size of the mean difference with larger Δf_{AB}. In the first epoch analysis, only the 8 ST A↓B↑ transition was significant (mean difference = -10.0 percentage points, $p = 0.038$, Table 5.25), but when the second interval post-transition was included, the A↓B↑ transition produced significant negative differences between adjacent intervals at 6 and 8 ST, again indicating substantial resetting (mean difference = -10.4 and -14.5 percentage points, $p < 0.05$, Table 5.26).

A similar pattern could be observed for the positive peak that followed A↑B↓ transitions, which reflected an accelerated rise in segregation level or 'overshoot'. Within the first epoch analysis, transitions in 4- and 6-ST conditions resulted in significant 'overshoot' (mean difference = 10.7 and 8.5 percentage points, $p < 0.05$, Table 5.25) which increased in magnitude when the second interval was included (mean difference = 19.7 and 21.5 percentage points, $p < 0.05$, Table 5.26). The 'overshoot' following the A↑B↓ transitions at 8 ST also reached significance in the second-epoch analysis (mean difference = 15.8 percentage points, $p = 0.009$, Table 5.26).

This increasing effect of the transitions over the 2-s post-change was also evident in the two corresponding ANOVAs for the 'HLH-'sequences (Tables 5.22 and 5.28). Whilst direction was significant as a main effect in both epoch analyses, Δf_{AB} × Transition Number also emerged as significant in the extended-interval analysis as early transitions tended to produce more positive peaks at lower Δf_{AB}s due to the increased scope for overshoot ($p = 0.032$, Table 5.28). The ceiling and floor effects of this range of Δf_{AB}s also accounted for the significant Δf_{AB} × Direction interaction term (p = 0.029, Table 5.28), as 'overshoot' was limited by near-complete build-up at higher Δf_{AB}s and resetting was limited by the lower segregation levels at Δf_{AB}=4 ST.

Individual transitions in 'LHL-' sequences had no significant effect within the 1-s post-transition interval, but when this interval was extended, the effect of both types of transition did become significant in the 4-ST case (p = 0.040 and p = 0.003, Table 5.26, cf. results for the corresponding conditions in Experiment 5). As for the 'HLH-' cases, A↓B↑ transitions tended to produce a negative peak (mean difference = -9.6 percentage points, p = 0.040, 5.26) and the A↑B↓ transition tended to produce a positive peak (mean difference = 9.9 percentage points, p = 0.003, 5.26). As evident in Figures 5.13-5.15, and unlike the 'HLH-' cases, the effect of transitions in 'LHL-' sequences diminished with increasing Δf_{AB}.

5.4.6.2 Triplet Structure

To compare the effects of triplet structure, the separate analysis for A↓B↑ and A↑B↓ should be considered. Despite producing visibly different difference score profiles, triplet structure did not produce a significant main effect in either the first or second epoch analysis of the separate A↓B↑ or A↑B↓ transitions. Despite this, the interaction term for Δf_{AB} and Triplet structure was significant in the first epoch analysis for the A↓B↑ transition (p < 0.001, Table 5.23), reflecting the reduction in the extent of resetting at higher Δf_{ABs}. It is notable that difference between adjacent time intervals tended to approach 0 in the second epoch, and this interaction term was no longer significant (p = 0.514, Table 5.29).

For the A↑B↓ transition in all configurations the overshoot produced was most prominent for the first transition in the 'B starts high' conditions perhaps due to the increased scope for a rapid rise in the rate of build-up, early on in the sequence. This was however most pronounced for the 'LHL-' configuration, where later A↑B↓ transitions tended not to produce any change in the existing rate of build-up. The same A↑B↓ transition produced overshoot at all transition points in the 'HLH-' sequence. This difference in the difference score profiles for both triplet structures was shown in the significant interaction term between Triplet Structure and Transition Number for both epoch analyses (p < 0.05, Tables 5.24and 5.30).

5.4.7 Discussion

In general, across frequency separation and condition, sequences with the 'HLH-' structure produced a more segregated percept than those with the 'LHL-' structure. The faster presentation rate or higher density of the high tones, or the higher average frequency of the triplet in 'HLH-' vs. 'LHL-' sequences, may have resulted in an increased tendency to perceive the sequences as segregated, although the reason for such an effect is not obvious. As expected, greater frequency separation also tended to increase segregation for all conditions.

Constant conditions where 'A' and 'B' subsets were presented at the same level produced the most integrated percept. When a constant difference was introduced between the subsets, so that 'A' was presented at a higher level than 'B', the rate of build-up increased and sequences were perceived as more segregated for both 'LHL-' and 'HLH-' configurations. This increase was still present, but was less pronounced, when the 'B' tones were presented at a higher level than the 'A' tones in an 'LHL-' configuration. However, when the 'B' tones were presented at a higher level than the 'A' tones within an 'HLH-' configuration, the increase was only present at 4 ST; for the 6- and 8-ST cases, there was a slight drop in segregation level when compared with the constant case. In summary, the difference between the outcomes for the 'LHL-' and 'HLH-' configurations is accentuated with increasing frequency separation.

The effects of anti-correlated changes tended to be stronger than those for the correlated change cases observed in Experiment 5, most likely because there was more than one factor changing at transition points (i.e., the levels of the 'A' and 'B' tones moved in opposite directions). The 'B' tone transitions tended to dominate but were weighted relative to frequency. As 'B' tone frequency was increased (with larger frequency separations) within the 'LHL-'triplet structure, the effect of the 'B' tone relative to the A tone appeared to drop, resulting in a limited effect of anti-correlated changes on streaming in that context.

If, as suggested earlier, it is the rising (low to high level) transition that causes the resetting evident in the correlated alternating cases, as for Experiments 4 and 5, the results from this experiment indicate that the effect is driven largely by 'B' tone changes, regardless of whether the sequence has an 'LHL-' or 'HLH-' configuration.

The alternating 'LHL-' cases were broadly comparable with the corresponding conditions in Experiment 5. In Experiment 5, as here, the falling transition of the 'B' (H) tone for the 4-ST case resulted in an 'overshoot' (segregation level exceeded the level of segregation at that time point for the constant cases) but this was less clear for the 6- and 8-ST cases. More consistent with the results of Experiment 5, is the resetting following B↑ (H) tone transitions at a frequency separation of 4 ST, an effect which diminishes with increasing frequency separation.

For the alternating 'HLH-' cases, the B↓ (L) tone transition induced a much more substantial overshoot at all frequency separations than was observed for any of the 'LHL-' cases. The B↑ (L) tone transitions induced clear resetting at all frequency separations.

5.5 General Discussion

The results of Experiments 5 and 6 demonstrate that resetting cannot be ascribed solely to a correlated change in the stimulus properties of both tone subsets. In both experiments, the anti-correlated changes associated with A↓B↑ transitions were also able to cause significant resetting. Furthermore, the anti-correlated changes associated with A↑B↓ transitions caused clear 'overshoot', like that first observed in response to the correlated change in timbre for pure-to-dyad transitions in Experiment 3 (Chapter 3).

Considered together, the effect of anti-correlated changes in the context of the two triplet configurations indicates that the directional effects of transitions depend on within-triplet position (A vs. B) rather than tone frequency (H vs. L). This outcome suggests that is the abrupt rise in level of the less numerous tones (subset B) that is mainly responsible for resetting. The greater overall segregation for the constant 'HLH-' cases may result from the twice faster presentation rate for the H tone in 'HLH-' than in 'LHL-' sequences. In both cases, the mechanisms responsible cannot be inferred based on these data alone. An increase in frequency separation could be observed to reduce both directional responses to sudden transitions in level for 'LHL-' alternating cases, but frequency separation was observed to have less effect on the responses to any of the transition types for 'HLH-' alternating cases .

These results appear to be more consistent with a neural mechanism based on subtractive adaptation, as discussed in the previous chapter, rather than a cognitive account based on cues for source origin. As described earlier, according to this account, build-up occurs in response to the falling amplitude in the response of adjacent, overlapping neural populations. The falling response results in reduced overlap between the two populations. As the initial response tended to be higher for the constant-difference (A-high, B-low) case in the 'HLH-'configuration than for the constant-difference (A-low, B-high) case, a A↓B↑ transition would cause a brief 'overshoot' as the neural population is less adapted to this segregation-promoting stimulus. In contrast, a A↑B↓ transition following an A-low B-high portion of the sequence would result in resetting or undershoot as considerable adaptation would have occurred prior to the transition. This explanation would also account for the smaller effects of transitions in 'LHL-'sequences, where the two constant difference cases tended to show similar patterns of build-up, limiting the scope for overshoot or resetting.

It should be noted that anti-correlated changes imply a relationship between the two subsets of sounds to which the auditory system might be sensitive—the changes in level occur at the same time, albeit in the opposite direction for the A and B subsets. Exploring further the role of factors signalling a relationship between subsets of sounds, and their perceptual consequences, would require a different approach from that taken here, such as introducing independent (random) changes into the two subsets or changing the properties of one subset but not the other.

Chapter 6

Segregation promotion using inducer tones with differences in level and Δf or accompanied by harmonic captors

6.1 Introduction

The experiments presented earlier in the thesis examined the effects of changes within a continuously monitored test sequence, demonstrating that an abrupt change in certain sequence properties (both correlated and anti-correlated) could result in resetting or overshoot of stream segregation. This chapter presents three experiments that used an inducer-test setup (outlined in Chapter 2) to explore the effect of the induction sequence (heard by listeners, but not responded to) on the perception of the subsequent test sequence. The effect of the prior sequence will be influenced by two factors first, the segregation-promoting effect of the inducer itself and, second, the extent to which that effect persists following an abrupt change in sequence properties at the inducer-test boundary.

These three experiments specifically focus on changes occurring at the inducer-test boundary. Use of the inducer-test setup, enabled changes to be applied only to one tone subset permitting investigation of segregation promotion by manipulating a single tone subset in the inducer sequence.

Experiment 7 looked at the effect of attenuating the level of individual tone subsets in an inducer, and Experiment 8 varied the frequency separation between tone subsets in an inducer. Experiment 9 introduced an additional harmonic complex, synchronous with the lower tone subset of an inducer, with the aim of capturing that subset into a separate stream.

The concept of stream biasing has been explored mostly by Snyder et al. (2008, 2009a, 2009b, 2011), typically by varying the frequency separation within an alternating tone sequence. These studies demonstrated that adjusting the frequency separation of a previous trial influenced the extent to which a subsequent trial was perceived as segregated when both trials were separated by a silent interval (>1.4 s). Snyder et al. (2008, 2009a, 2009b, 2011) presented sequences of 'ABA-' triplets separated by a silent interval. At the end of each trial, listeners were prompted to report their overall perception of that trial (whether 1 or 2 streams) by pressing the appropriate key (2008) or by to pressing and holding the appropriate key throughout the trial and release during the silent intervals (2009).

The investigators noted that a smaller frequency separation in the previous trial consistently led to a more segregated percept of the current trial, whilst a larger separation in the previous trial produced a more integrated percept of the current trial. The promotion of segregation by a prior stimulus, hypothesised to result from 'stream capture' (cf. Bregman and Rudincky) has also been explored using a constant-frequency inducer (Bregman and Rudnicky, 1975; Beauvois and Meddis, 1997; Rogers and Bregman, 1998; Roberts, Glasberg, and Moore, 2008; Haywood and Roberts 2010, 2011, 2013). Presentation of a repeating single-frequency inducer, matched to the level of one of the tone subsets of a subsequent alternating-frequency sequence, results in a highly segregated percept in the following test sequence. Rogers and Bregman (1993) used a 4.8-s inducer followed by a standard 1.2-s test sequence of alternating tones (400 ms/cycle) to measure the effect of a single repeating tone on the test sequence percept. They observed that the constant frequency inducer most effectively induced segregation when it was matched in tone density and number of onsets with the corresponding tone subset of the test sequences, demonstrating that increased stimulation in the frequency region of one subset did not necessarily induce greater segregation in the test sequence. These studies required listeners to make one-off judgments of the test sequence on each trial.

Rogers and Bregman (1993) suggested that this resulted from 'capture' of the tone subset into the pre-existing stream of constant frequency tones, but an alternative theory (Snyder et al. 2008, 2009a, 2009b, 2011; Thompson, Carlyon, and Cusack, 2011) is that this segregation promotion may be a result of selective adaptation of frequency-sensitive neurons or frequency-shift detectors. However, there were clear differences between the results obtained by Haywood and Roberts (2013) and Snyder et al. (2008). Unlike the modest effect of a prior constant-frequency trial on the subsequent percept observed by Snyder et al. (2008), Haywood and Roberts (2013) noted that the segregation-promoting effect of the constant frequency inducer was strongest at the start of the 12-s sequence that followed. This effect diminished over the course of the sequence, most obviously for the 9-ST frequency separation. Haywood and Roberts (2013) argued that this discrepancy was a result of the silent interval employed by Snyder et al (2008), arguing that this rapid process was more representative of perceptual capture rather than of a slower neural adaptation process or comparison of current and prior percepts.

Whilst the investigations of segregation promotion discussed above have varied the properties of a constant-frequency inducer to some extent (with respect to tone duration, onsets and rhythm), there has been limited observation of other inducer properties that may promote segregation in a following test-sequence. Level differences in an inducer were explored by Rogers and Bregman (1998) (as described in Chapter 4), but it is notable that all changes in level were applied to both A and B subsets, for which abrupt changes at the inducer-test boundary tended to result in a resetting of segregation rather than promotion of segregation. In view of this, the experiments presented in this chapter attempted to induce segregation either by varying a single tone subset in level (Experiment 7) and frequency (Experiment 8) or by capturing out a subset using an additional harmonically related complex (Experiment 9).

6.2 Experiment 7: Level differences between tone subsets in an inducer

Experiment 7 used a 2-s inducer followed by a 20-s ‘ABA-’ test sequence (totalling 55 ‘ABA-’ triplets) to explore the effect of level differences within the inducer triplets (between ‘A’ and ‘B’ tones) on the perception of the test sequence. Either the ‘A’ or ‘B’ tones were attenuated by 0, 6, 12, or 24 dB. A silent-inducer case, no-attenuation case, and cases where either ‘A’ or ‘B’ were completely attenuated were included to compare the ‘capturing effect’ of each tone subset (cf. Bregman and Rudnicky, 1975). Given that the ‘A’ tone repetition rate was twice that of the ‘B’ tones, each tone subset was attenuated in turn, to establish if the frequency and tone density would affect the outcome. Intensity ranged between 37-73 dB SPL, and the test sequence tones were set to 73 dB SPL.

6.2.1 Method

The method and procedure for this experiment were as described in the General Methods (Chapter 2). Listeners were required to continuously monitor the stimulus and instructed not to respond during the inducer sequence, waiting until the message on the screen changed from ‘Please wait’ to ‘Please respond’, to begin responding (as for the continuous assessment procedure.)

6.2.2 Conditions

1. *Silent inducer:* 2-s of silence
2. *0 dB attenuation (reference case):* Inducer identical to standard test sequence
3. *6 dB attenuation on B:* B tones in inducer attenuated by 6 dB relative to A tones
4. *12 dB attenuation on B:* B tones in inducer attenuated by 12 dB relative to A tones
5. *24 dB attenuation on B:* B tones in inducer attenuated by 24 dB relative to A tones
6. *∞ dB attenuation on B:* B tones in inducer are absent (i.e., replaced with silence), resulting in a constant frequency A-only inducer

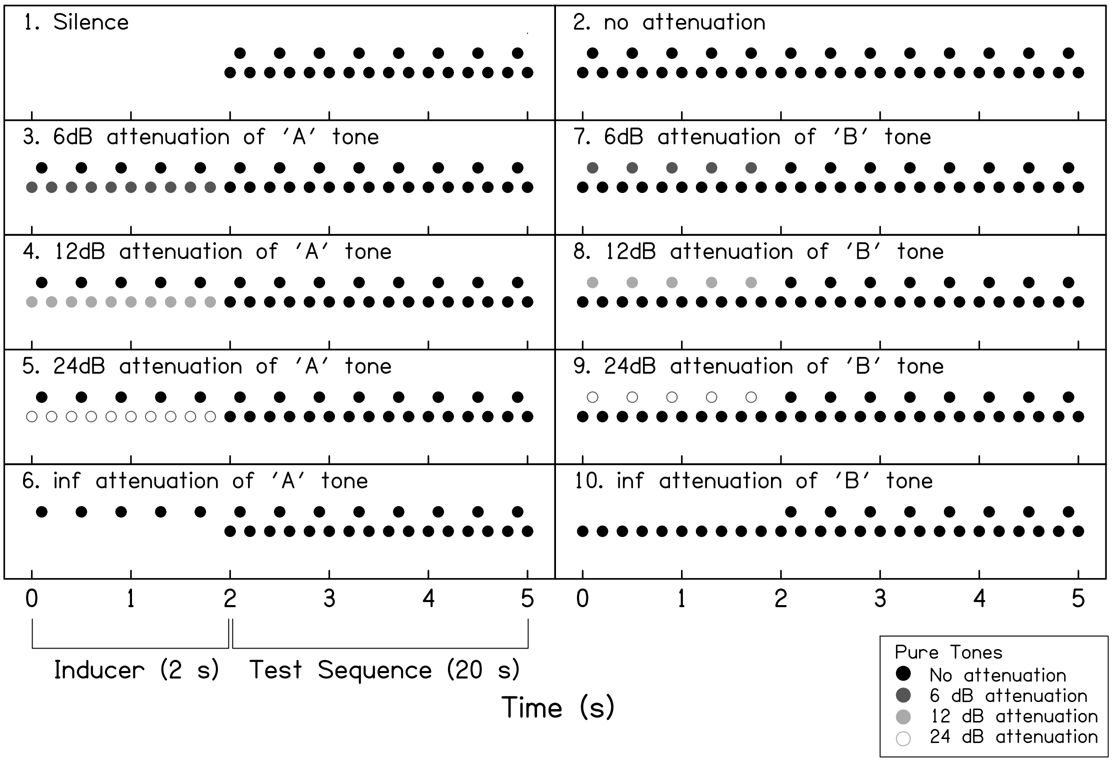

FIGURE 6.1: Illustration of the conditions (1-10) used in Experiment 7.

7. *6 dB attenuation on A:* A tones in inducer attenuated by 6 dB relative to A tones
8. *12 dB attenuation on A:* A tones in inducer attenuated by 12 dB relative to A tones
9. *24 dB attenuation on A:* A tones in inducer attenuated by 24 dB relative to A tones
10. ∞ *dB attenuation on A:* A tones in inducer are absent (i.e., replaced with silence), resulting in a constant frequency B-only inducer

6.2.3 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As described in Chapter 2, all conditions were presented during each of the 10 blocks over two sessions (5 blocks in each session). As before Δf_{AB} was set at 4-, 6- and 8-ST.

6.2.4 Results

The results of Experiment 7 were analysed using two three-way repeated measures ANOVAs and the corresponding pairwise comparisons. The first ANOVA (summarised

Table 6.1: Three-way repeated measures ANOVA comparing the first 10 time intervals.

Factor	*df*	*F*	*p*	η_p^2
Δf_{AB}	**(2,22)**	**66.037**	**<0.001**	**0.857**
Condition	**(9,99)**	**14.017**	**<0.001**	**0.560**
Time Interval	**(9,99)**	**15.859**	**<0.001**	**0.590**
Δf_{AB} × Condition	(18,198)	1.458	0.109	0.117
Δf_{AB} × **Time Interval**	**(18,198)**	**3.234**	**<0.001**	**0.227**
Condition × Time Interval	**(81,891)**	**2.690**	**<0.001**	**0.196**
Δf_{AB} × Condition × Time Interval	**(162,1782)**	**1.866**	**<0.001**	**0.145**

Table 6.2: Pairwise Comparison of A-B frequency separations for the first 10 time intervals across all conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	*p*
4	**6**	**-23.8**	**2.72**	**<0.001**
	8	**-42.8**	**4.93**	**<0.001**
6	**4**	**23.8**	**2.72**	**<0.001**
	8	**-19.0**	**3.16**	**<0.001**
8	**4**	**42.8**	**4.93**	**<0.001**
	6	**19.0**	**3.16**	**<0.001**

in Table 6.1) analysed the first 10 time-intervals, and the second (summarised in Table 6.6) included the final 9 time-intervals. This was to permit examination of the effect of condition separately for the initial rapid phase of build-up and second slower phase (cf. Anstis and Saida, 1985).

In general, listeners' perceptions of the sequences tended to become more segregated over time, and as expected, the initial rate of build-up was accelerated at higher Δf_{ABs} shown in the significant main effects of Δf_{AB}, Condition, and Time Interval (p < 0.001, Tables 6.1 and 6.6). The interaction terms Δf_{AB} × Time Interval and Condition × Time Interval were also all highly significant (p < 0.001, Tables 6.1 and 6.6). The initial and final analyses mainly differed in that the three-way interaction term was significant in the former case ($p < 0.001$, Table 6.5), but not the latter ($p = 0.977$, Table 6.10). Consistent with this, the curves for conditions tended be highly segregated and converge beyond the 10-s time-point (as shown in Figures 6.2 to 6.4).

6.2.4.1 Δf_{AB}

The significant main effect of Δf_{AB} was consistent with the observed increase in the extent of segregation at higher frequency separations across all conditions. This pattern

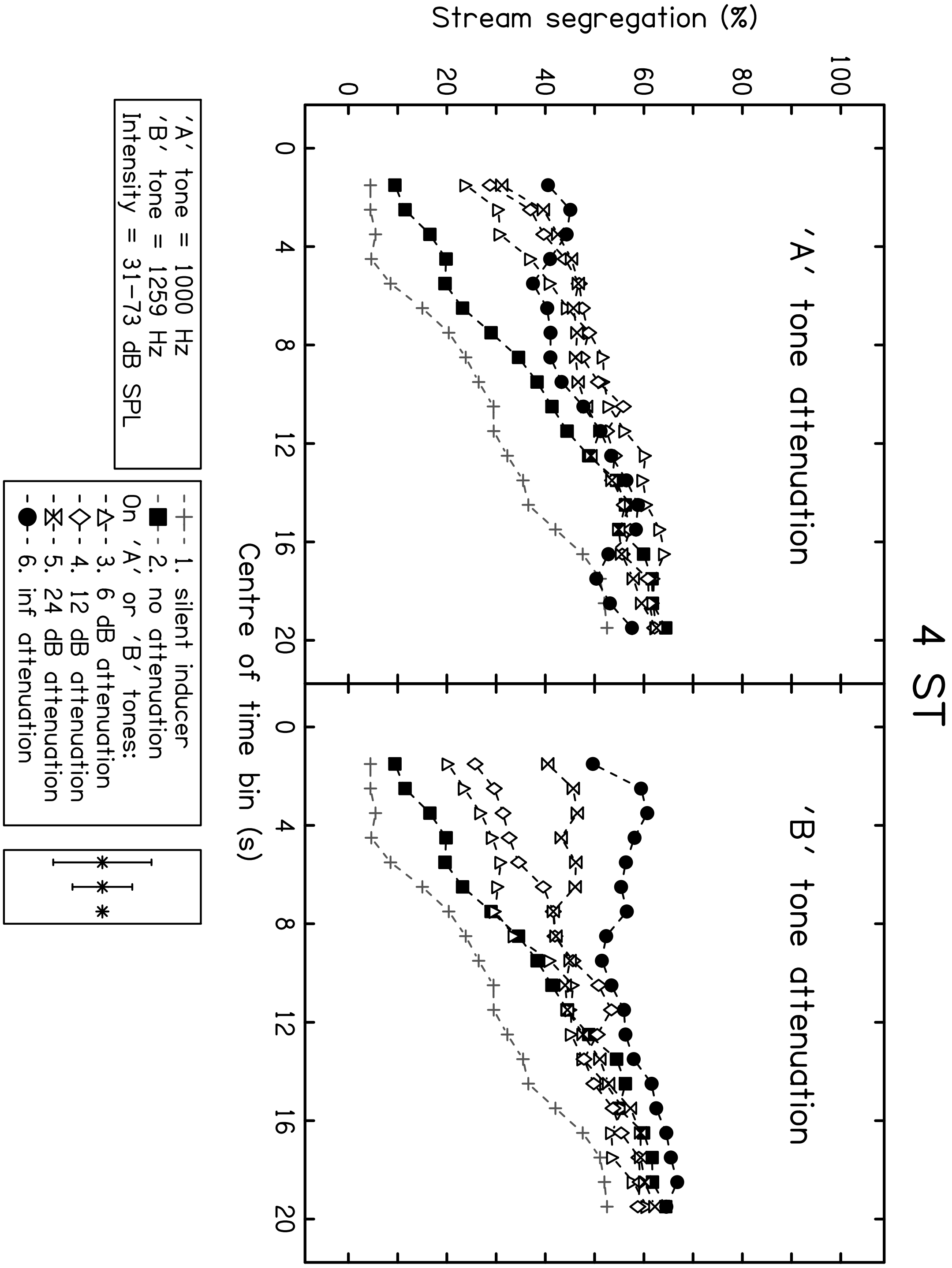

Figure 6.2: The stream segregation data averaged across listeners from Experiment 7 displaying the pattern of build-up over the 20-s test sequence (following a 2-s inducer) for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

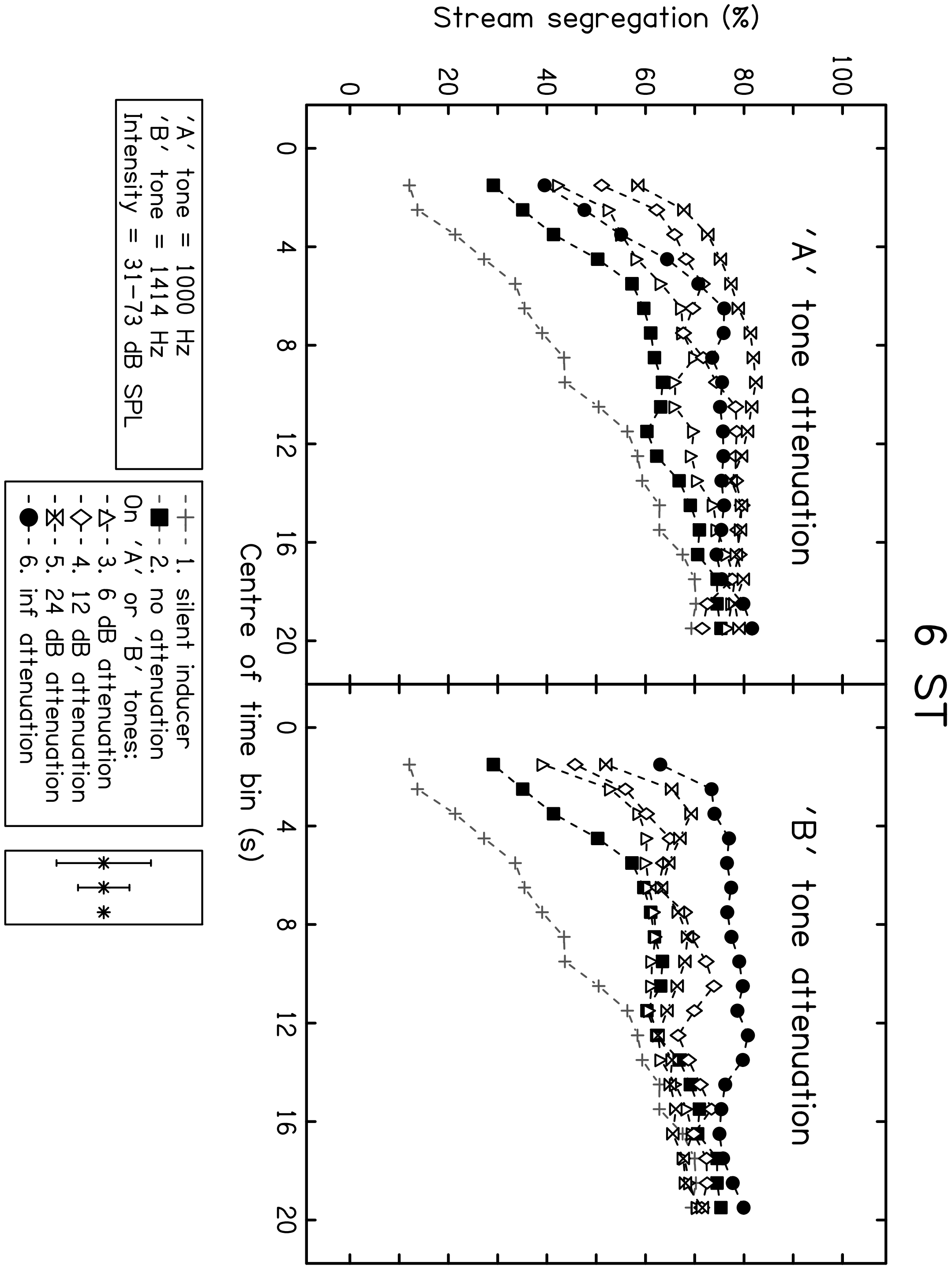

FIGURE 6.3: The stream segregation data averaged across listeners from Experiment 7 displaying the pattern of build-up over the 20-s test sequence (following a 2-s inducer) for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

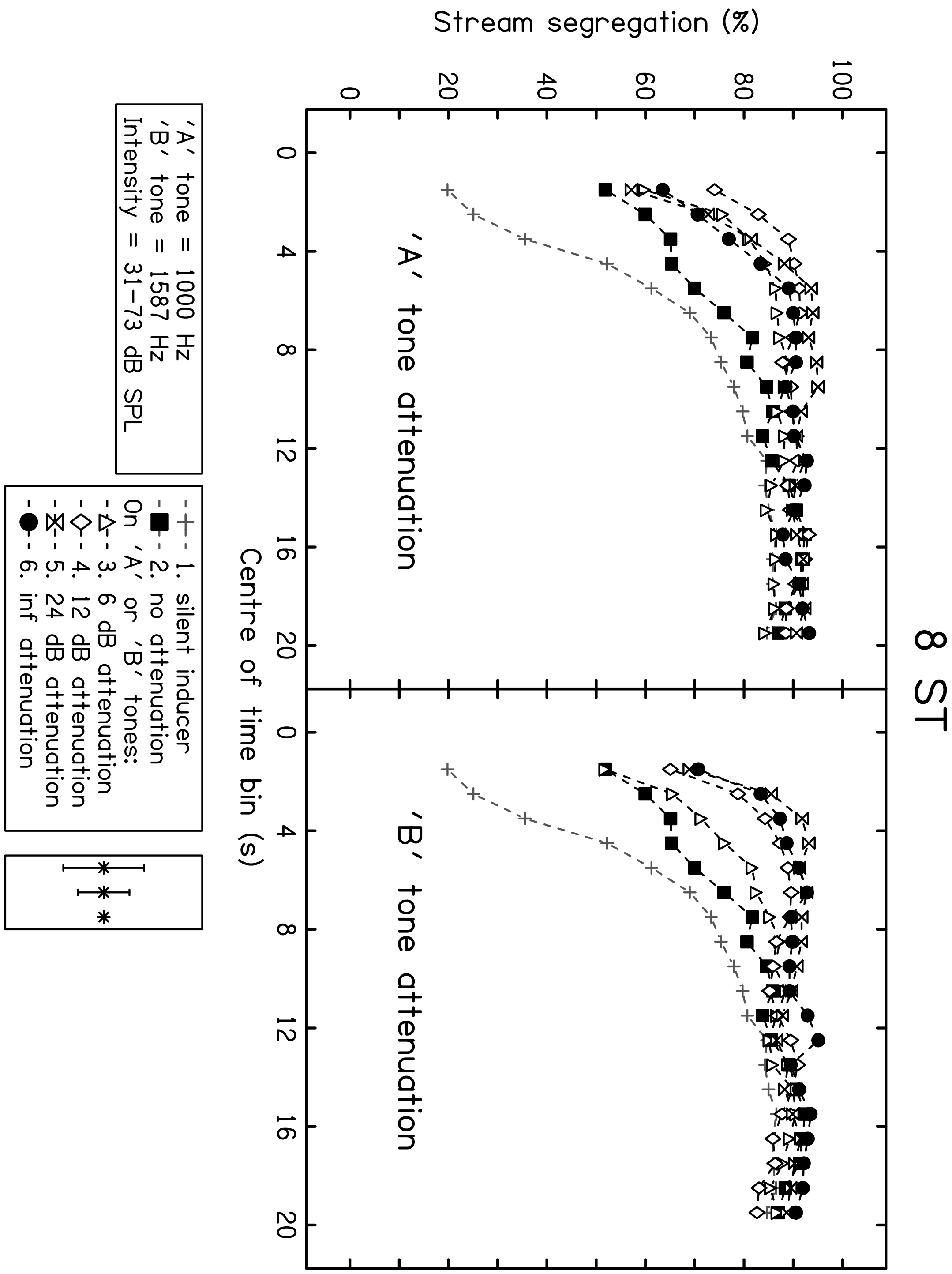

FIGURE 6.4: The stream segregation data averaged across listeners from Experiment 7 displaying the pattern of build-up over the 20-s test sequence (following a 2-s inducer) for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

Table 6.3: Pairwise Comparison of Conditions 1-5 against all other conditions.

(I) Condition	(J) Condition	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-15.2**	**2.5**	<**0.001**
	3	**-21.1**	**3.7**	<**0.001**
	4	**-27.3**	**4.0**	<**0.001**
	5	**-31.6**	**5.4**	<**0.001**
	6	**-38.3**	**5.4**	<**0.001**
	7	**-27.2**	**4.2**	<**0.001**
	8	**-32.4**	**5.2**	<**0.001**
	9	**-34.2**	**5.6**	<**0.001**
	10	**-29.2**	**6.4**	**0.001**
2	**1**	**15.2**	**2.5**	<**0.001**
	3	-6.0	3.6	0.127
	4	**-12.2**	**3.8**	**0.008**
	5	**-16.4**	**5.1**	**0.008**
	6	**-23.1**	**5.1**	**0.001**
	7	**-12.0**	**2.9**	**0.002**
	8	**-17.2**	**4.5**	**0.003**
	9	**-19.1**	**5.4**	**0.005**
	10	**-14.1**	**6.3**	**0.047**
3	**1**	**21.1**	**3.7**	<**0.001**
	2	6.0	3.6	0.127
	4	**-6.2**	**1.9**	**0.008**
	5	**-10.5**	**3.3**	**0.009**
	6	**-17.1**	**3.6**	**0.001**
	7	-6.0	3.2	0.088
	8	**-11.3**	**3.6**	**0.010**
	9	**-13.1**	**4.8**	**0.020**
	10	-8.1	5.5	0.172
4	**1**	**27.3**	**4.0**	<**0.001**
	2	**12.2**	**3.8**	**0.008**
	3	**6.2**	**1.9**	**0.008**
	5	-4.3	3.0	0.187
	6	**-11.0**	**3.0**	**0.004**
	7	0.2	2.9	0.960
	8	-5.1	3.0	0.115
	9	-6.9	4.3	0.138
	10	-1.9	4.6	0.687
5	**1**	**31.6**	**5.4**	<**0.001**
	2	**16.4**	**5.1**	**0.008**
	3	**10.5**	**3.3**	**0.009**
	4	4.3	3.0	0.187
	6	**-6.7**	**1.6**	**0.002**
	7	4.4	3.5	0.231
	8	-0.8	3.7	0.831
	9	-2.6	4.4	0.564
	10	2.4	4.4	0.599

Table 6.4: Pairwise Comparison of Conditions 6-10 against all other conditions.

(I) Condition	(J) Condition	Mean Difference [I-J] (%)	Std. Error (%)	p
6	**1**	**38.2**	**5.4**	**<0.001**
	2	**23.1**	**5.1**	**<0.001**
	3	**17.1**	**3.6**	**<0.001**
	4	**11.0**	**3.0**	**0.004**
	5	**6.7**	**1.6**	**0.002**
	7	**11.1**	**3.5**	**0.009**
	8	5.9	3.9	0.162
	9	4.1	5.0	0.431
	10	9.0	5.2	0.110
7	**1**	**27.2**	**4.2**	**<0.001**
	2	**12.0**	**2.9**	**0.002**
	3	6.0	3.2	0.088
	4	-0.2	2.9	0.960
	5	-4.4	3.5	0.231
	6	**-11.1**	**3.5**	**0.009**
	8	-5.2	2.8	0.090
	9	-7.0	4.1	0.115
	10	-2.1	5.4	0.712
8	**1**	**32.4**	**5.2**	**<0.001**
	2	**17.2**	**4.5**	**0.003**
	3	**11.3**	**3.6**	**0.010**
	4	5.1	3.0	0.115
	5	0.8	3.7	0.831
	6	-5.9	3.9	0.162
	7	5.2	2.8	0.090
	9	-1.8	2.2	0.421
	10	3.2	3.9	0.436
9	**1**	**34.2**	**5.6**	**<0.001**
	2	**19.1**	**5.4**	**0.005**
	3	**13.1**	**4.8**	**0.020**
	4	6.9	4.3	0.138
	5	2.6	4.4	0.564
	6	-4.1	5.0	0.431
	7	7.0	4.1	0.115
	8	1.8	2.2	0.421
	10	5.0	3.3	0.164
10	**1**	**29.2**	**6.4**	**0.001**
	2	**14.1**	**6.3**	**0.047**
	3	8.1	5.5	0.172
	4	1.9	4.6	0.687
	5	-2.4	4.4	0.599
	6	-9.0	5.2	0.110
	7	2.1	5.4	0.712
	8	-3.2	3.9	0.436
	9	-5.0	3.3	0.164

TABLE 6.5: Pairwise Comparison of the first 10 time intervals when averaged across all conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	**-8.8**	**0.8**	**<0.001**
	3	**-13.1**	**1.3**	**<0.001**
	4	**-16.2**	**1.6**	**<0.001**
	5	**-18.7**	**1.9**	**<0.001**
	6	**-20.5**	**2.3**	**<0.001**
	7	**-21.7**	**3.0**	**<0.001**
	8	**-22.6**	**3.6**	**<0.001**
	9	**-23.8**	**4.2**	**<0.001**
	10	**-25.1**	**4.5**	**<0.001**
10	**1**	**25.1**	**4.5**	**<0.001**
	2	**16.3**	**4.9**	**0.007**
	3	**12.0**	**4.8**	**0.031**
	4	8.8	4.4	0.070
	5	6.3	3.6	0.104
	6	4.6	2.7	0.113
	7	3.3	1.8	0.087
	8	2.5	1.2	0.060
	9	**1.3**	**0.5**	**0.019**

TABLE 6.6: Three-way repeated measures ANOVA comparing the last 9 time intervals.

Factor	df	F	p	η_p^2
Δf_{AB}	**(2,22)**	**48.369**	**<0.001**	**0.815**
Condition	**(9,99)**	**5.462**	**<0.001**	**0.332**
Time Interval	**(8,88)**	**7.512**	**<0.001**	**0.406**
Δf_{AB} × Condition	(18,198)	1.267	0.213	0.103
Δf_{AB} × **Time Interval**	**(16,176)**	**6.091**	**<0.001**	**0.356**
Condition × Time Interval	**(72,792)**	**2.129**	**<0.001**	**0.162**
Δf_{AB} × Condition × Time Interval	(144,1584)	0.771	0.977	0.066

TABLE 6.7: Pairwise Comparison of A-B frequency separations for the last 9 time intervals across all conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-17.1**	**2.83**	**<0.001**
	8	**-33.8**	**4.54**	**<0.001**
6	4	**17.1**	**2.83**	**<0.001**
	8	**-16.7**	**2.60**	**<0.001**
8	4	**33.8**	**4.54**	**<0.001**
	6	**16.7**	**2.60**	**<0.001**

Table 6.8: Pairwise Comparison of Conditions 1-5 against all other conditions for the last 9 time intervals.

(I) Conditions	(J) Conditions	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-7.8**	**2.2**	**0.004**
	3	-5.1	2.6	0.081
	4	-6.9	3.2	0.051
	5	-6.4	3.8	0.121
	6	**-13.5**	**3.6**	**0.003**
	7	**-10.1**	**2.7**	**0.003**
	8	**-11.1**	**2.7**	**0.002**
	9	**-11.6**	**4.2**	**0.020**
	10	**-10.4**	**3.8**	**0.020**
2	**1**	**7.8**	**2.2**	**0.004**
	3	2.8	2.2	0.239
	4	0.9	2.7	0.737
	5	1.4	3.0	0.634
	6	**-5.7**	**2.48**	**0.042**
	7	-2.3	1.6	0.188
	8	-3.3	1.7	0.083
	9	-3.8	3.5	0.303
	10	-2.5	2.7	0.371
3	1	5.1	2.6	0.077
	2	-2.8	2.2	0.239
	4	-1.9	2.1	0.397
	5	-1.3	2.2	0.567
	6	**-8.4**	**2.5**	**0.006**
	7	**-5.1**	**1.9**	**0.024**
	8	**-6.1**	**1.5**	**0.002**
	9	-6.6	3.5	0.088
	10	**-5.3**	**2.4**	**0.045**
4	1	6.9	3.2	0.051
	2	-0.9	2.7	0.737
	3	1.9	2.1	0.397
	5	0.5	1.3	0.691
	6	**-6.6**	**1.4**	**0.001**
	7	-3.2	1.7	0.087
	8	**-4.2**	**1.3**	**0.007**
	9	-4.7	2.2	0.052
	10	-3.5	1.7	0.060
5	1	6.4	3.8	0.121
	2	-1.4	3.0	0.634
	3	1.3	2.2	0.567
	4	-0.5	1.3	0.691
	6	**-7.1**	**1.2**	**<0.001**
	7	**-3.7**	**1.6**	**0.035**
	8	**-4.7**	**1.7**	**0.015**
	9	**-5.3**	**2.3**	**0.043**
	10	**-4.0**	**1.2**	**0.005**

TABLE 6.9: Pairwise Comparison of Conditions 6-10 against all other conditions for the last 9 time intervals.

(I) Conditions	(J) Conditions	Mean Difference [I-J] (%)	Std. Error (%)	p
6	**1**	**13.5**	**3.6**	**0.003**
	2	**5.7**	**2.5**	**0.042**
	3	**8.4**	**2.5**	**0.006**
	4	**6.6**	**1.4**	**0.001**
	5	**7.1**	**1.2**	**<0.001**
	7	**3.4**	**1.3**	**0.028**
	8	2.4	1.6	0.154
	9	1.9	2.3	0.432
	10	**3.1**	**1.0**	**0.012**
7	**1**	**10.1**	**2.7**	**0.003**
	2	2.3	1.6	0.188
	3	**5.1**	**1.9**	**0.024**
	4	3.2	1.7	0.087
	5	**3.7**	**1.6**	**0.035**
	6	**-3.4**	**1.3**	**0.028**
	8	-1.0	1.2	0.418
	9	-1.5	2.7	0.586
	10	-0.2	1.6	0.883
8	**1**	**11.1**	**2.7**	**0.002**
	2	3.3	1.7	0.083
	3	**6.1**	**1.5**	**0.002**
	4	**4.2**	**1.3**	**0.007**
	5	**4.7**	**1.7**	**0.015**
	6	-2.4	1.6	0.154
	7	1.0	1.2	0.418
	9	-0.5	2.5	0.840
	10	0.8	1.6	0.652
9	**1**	**11.6**	**4.3**	**0.020**
	2	3.8	3.5	0.303
	3	6.6	3.5	0.088
	4	4.7	2.2	0.052
	5	**5.3**	**2.3**	**0.043**
	6	-1.9	2.3	0.432
	7	1.5	2.7	0.586
	8	0.5	2.5	0.840
	10	1.3	2.6	0.636
10	**1**	**10.4**	**3.8**	**0.020**
	2	2.5	2.7	0.371
	3	**5.3**	**2.4**	**0.045**
	4	3.5	1.7	0.060
	5	**4.0**	**1.1**	**0.005**
	6	**-3.1**	**1.0**	**0.012**
	7	0.2	1.6	0.883
	8	-0.8	1.6	0.652
	9	-1.3	2.6	0.636

TABLE 6.10: Pairwise Comparison of the last 9 time intervals when averaged across all conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	**2**	**-0.9**	**0.2**	**0.002**
	3	**-1.7**	**0.7**	**0.033**
	4	**-3.1**	**0.9**	**0.005**
	5	**-4.2**	**0.9**	**0.001**
	6	**-4.5**	**1.2**	**0.003**
	7	**-5.2**	**1.5**	**0.005**
	8	**-5.3**	**1.8**	**0.012**
	9	**-5.8**	**1.8**	**0.007**
9	**1**	**5.8**	**1.8**	**0.007**
	2	**4.9**	**1.7**	**0.015**
	3	**4.1**	**1.6**	**0.025**
	4	2.7	1.5	0.092
	5	1.5	1.3	0.251
	6	1.4	1.0	0.190
	7	0.6	0.7	0.390
	8	0.5	0.3	0.117

was preserved over the full course of the tone sequence pairwise comparisons at 4, 6, and 8 ST remained significantly different for both the initial 10-s and final 9-s analyses (mean difference = 19.0 to 42.8 percentage points, $p < 0.001$, Table 6.2 and mean difference = 16.7 to 33.8 percentage points, $p < 0.001$, Table 6.7). This elevation of the overall extent of segregation at larger Δf_{ABs} appeared to be present for all conditions, shown in the failure of the Δf_{AB} × Condition interaction term to reach significance in either analysis ($p = 0.109$, Table 6.2 and $p = 0.213$, Table 6.6).

6.2.4.2 Time Interval

Pairwise-comparisons of individual 1-s time bins within the initial 10 s period revealed a significantly lower initial segregation level when compared to all other time intervals (mean difference = -8.8 to -25.1 percentage points, $p > 0.001$, Table 6.5). However, the difference between the 10-11 s interval and preceding time-points ceased to be significant after the 3-4 s interval, reflecting the initially rapid rate of build-up that slowed as a high extent of segregation was reached. Over the final analysis, the last time interval was significantly higher than only the first three intervals of the latter time period (mean difference < 5.8% percentage points, $p > 0.05$, Table 6.5).

6.2.4.3 Condition

As Condition displayed a main effects in both analyses ($p < 0.001$, Tables 6.1 and 6.6), consideration of the pairwise comparisons for both the initial and final portion of the test sequence. As visible in Figures 6.2 to 6.4, the silent inducer and no-attenuation conditions produced the most integrated perception of the test sequence across all three Δf_{ABs} (Table 6.3).

As expected, the no-attenuation case induced slightly more segregation in the test sequence than the silent case (mean difference = 15.2 percentage points, $p < 0.001$, Table 6.3). The attenuation cases induced increasing segregation with greater attenuation of each tone subset; the mean difference between the standard case and all attenuation cases ranged between -6.0 and 19.1 percentage points, with only the 6 dB 'A' tone attenuation case failing to be significantly different from the standard case (Table 6.3). Whilst the segregation-promoting effect of attenuation appeared more distinct with the 'B' attenuation cases than the 'A' attenuation cases (Figures 6.2 to 6.4), the pairwise comparison of the silent case and the infinite 'A' attenuation case (mean difference = 38.3 percentage points, $p < 0.001$, Table 6.3) showed greater differences than the comparison with the infinite 'B' attenuation case (mean difference = 29.2 percentage points, $p < 0.001$, Table 6.3).

The pairwise comparisons of conditions over the last 9 time intervals reflected the converging of the stream segregation curves during the final portion of the test sequence. The silent case remained significantly lower than the no attenuation case (mean difference = 7.8 percentage points, $p = 0.004$, Table 6.8) and from all 'B' tone attenuation cases (mean difference = 10.1 to 11.6 percentage points, $p < 0.001$, Table 6.8). However the differences between the silent and 'A' attenuation cases were only significant for the infinite 'A' attenuation case (mean difference = 13.5 percentage points, $p = 0.003$, Table 6.8).

6.2.5 Discussion

Broadly comparable patterns of effect of attenuation were observed for both tone subsets, although the effects were less distinct for the 'A' tone attenuation cases. This may be attributable to the reduced tone density and slower repetition rate of the remaining 'B' tones in the inducer. In general, the silent inducer case was simply a time-shifted version of the standard case (as build-up occurred over the 2-s 'ABA-' inducer sequence), and the expected capturing effect was evident for both the infinite attenuation cases.

For the attenuated tone conditions, the pattern of results varied based on whether the attenuation was applied to 'A' or 'B' tones. In the case of 'B' tone attenuation, as level of attenuation increased the percept changed systematically from a lower initial level of segregation (close to the no-attenuation case) to a more segregated percept (similar to the infinite-attenuation case). The rate of build-up was highest for the least attenuated cases, so that all curves converged by 20-s.

This pattern was evident for all frequency separations, although for 8 ST ceiling effects minimised the differences between the larger attenuation cases. The 'B' infinite attenuation case is analogous to the constant frequency inducer employed by Haywood and Roberts (2013) both were 2-s inducers composed of fast repeating, low frequency tones and consistent with those results, induced the greatest initial level of segregation. This was attributed to the 'capture' of test sequence tones into the pre-existing stream of constant frequency inducer tones. Although, unlike Haywood and Roberts (2013), there was no evidence of a decline in segregation over the first 10 s for larger frequency separations, the maximum frequency separation used in this study was 8-ST. Haywood and Roberts (2013) observed this effect mainly in the 9-ST case, which may account for the difference. These differences could be explained by the differences in A and B tone properties. The 'A' tone is low frequency and faster repeating. The 'B' tone is high frequency and repeats at a slower rate. This means that for infinite attenuation cases, the 'A' tone attenuated inducer is a high frequency tone (of either 1259, 1414 or 1587 Hz) repeating at a slower rate (3.33 Hz). In the 'B' tone infinite attenuation case, the inducer is a low frequency (1 kHz) A 12-dB attenuation of one subset does not prevent pitch alternations occurring, but nonetheless leads to increased initial segregation. This may imply that it is level transition for one subset at the inducer-test boundary, rather than the reduced level per se that leads to this effect.

In summary, Experiment 7 demonstrated that increasing segregation levels in a test sequence could be induced by attenuating either tone subset in an inducer. The effects were not just dependent on triplet structure, both high and low tone subsets promoted segregation - potentially through the capture of corresponding tones in the test sequence into a pre-existing stream.

As this investigation used attenuation of a subset, future studies could involve increases in level within one tone subset, to establish if the results observed here were direction-sensitive or caused by an increase in 'perceptual distance' between tone subsets.

6.3 Experiment 8: Varying Δf_{AB} of an inducer sequence relative to Δf_{AB} of the test sequence

Following on from the clear effect of attenuating a tone subset in Experiment 7, Experiment 8 again attempted to bias listeners towards perceiving segregation, by shifting one subset of inducer tones further away or closer to the other inducer tones in the frequency domain. Varying the frequency separation between 'H' and 'L' tones in a 'HLH-' inducer sequence (Δf_i), the experiment attempted to determine whether moving subsets closer together or further apart, relative to the separation used in the test sequence (Δf_t), would either disrupt potential capture of the fixed tone subset or affect build-up of the test sequence.

As the rate of build-up tended to slow considerably beyond the 12-s point for Experiment 7, this investigation used the 2-s inducer followed by a shorter 12-s 'HLH-' sequence (5 + 30 triplets). The sequences were presented binaurally at 70 dB SPL, once again with the Δf_{AB} of the test sequence at 4, 6, and 8 ST. This time, the higher frequency 'H' subset was fixed at 1 kHz, and the lower frequency 'L' subset varied according to Δf_{AB}.

6.3.1 Conditions and Hypotheses

The induction sequences used were as follows:

1. *Silence*
2. *H-H-*: 100-ms high tones only; low tones replaced by silence of equal duration.

3. *HHH-*: $\Delta f_i = 0$, i.e., the 'L' tone is shifted up to the H-tone frequency, producing a repeating, concatenated sequence of 3 100-ms 'H' tones followed by a 100-ms silence.

4. *HLH-*: $\Delta f_i = 0.5 \times \Delta f_t$, i.e., the frequency of the 'L' tone in the inducer is shifted higher so that the Δf_i is half that of Δf_t (in semitones).

5. *HLH-*: $\Delta f_i = \Delta f_t$, i.e., the inducer is identical to the test sequence.

6. *HLH-*: $\Delta f_i = 1.5 \times \Delta f_t$, i.e., the frequency of the 'L' tone in the inducer is shifted lower so that the Δf_i is 1.5× that of Δf_t (in semitones).

According to the observations of Snyder at al. (2008, 2009), it would be expected that when $\Delta f_i = 1.5 \times \Delta f_t$ there would be a less segregated perception of the test sequence relative to when $\Delta f_i = \Delta f_t$. Whereas when $\Delta f_i = 0.5 \times \Delta f_t$ the inducer would produce a more segregated test sequence than the standard case. Additionally, the preservation of rhythm when $\Delta f_i = 0$ (i.e., an 'HHH-' inducer) should result in a comparably high segregation level (c.f. Snyder 2011), although the increased tone density and number of onsets of the 'H' tone might reduce the degree of subsequent build-up (c.f. Rogers and Bregman, 2003). It may be observed that, as for Experiment 7, the increased perceptual distance between 'H' and 'L' tones in the frequency domain may encourage segregation of the static 'H' tones when $\Delta f_i = 1.5 \times \Delta f_t$.

6.3.2 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As described in Chapter 2, all conditions were presented during each of the 10 blocks over a single session.

6.3.3 Results

As for Experiment 7, the results of Experiment 8 were analysed with the use of a three-way repeated measures ANOVA and the corresponding pairwise comparisons. The shorter test-sequence durations required analysis with only a single analysis. The results are shown for each Δf_{AB} in Figures 6.6-6.8. The summary of the ANOVA is shown in Table 6.11), and the pairwise comparisons of Condition in Table 6.12

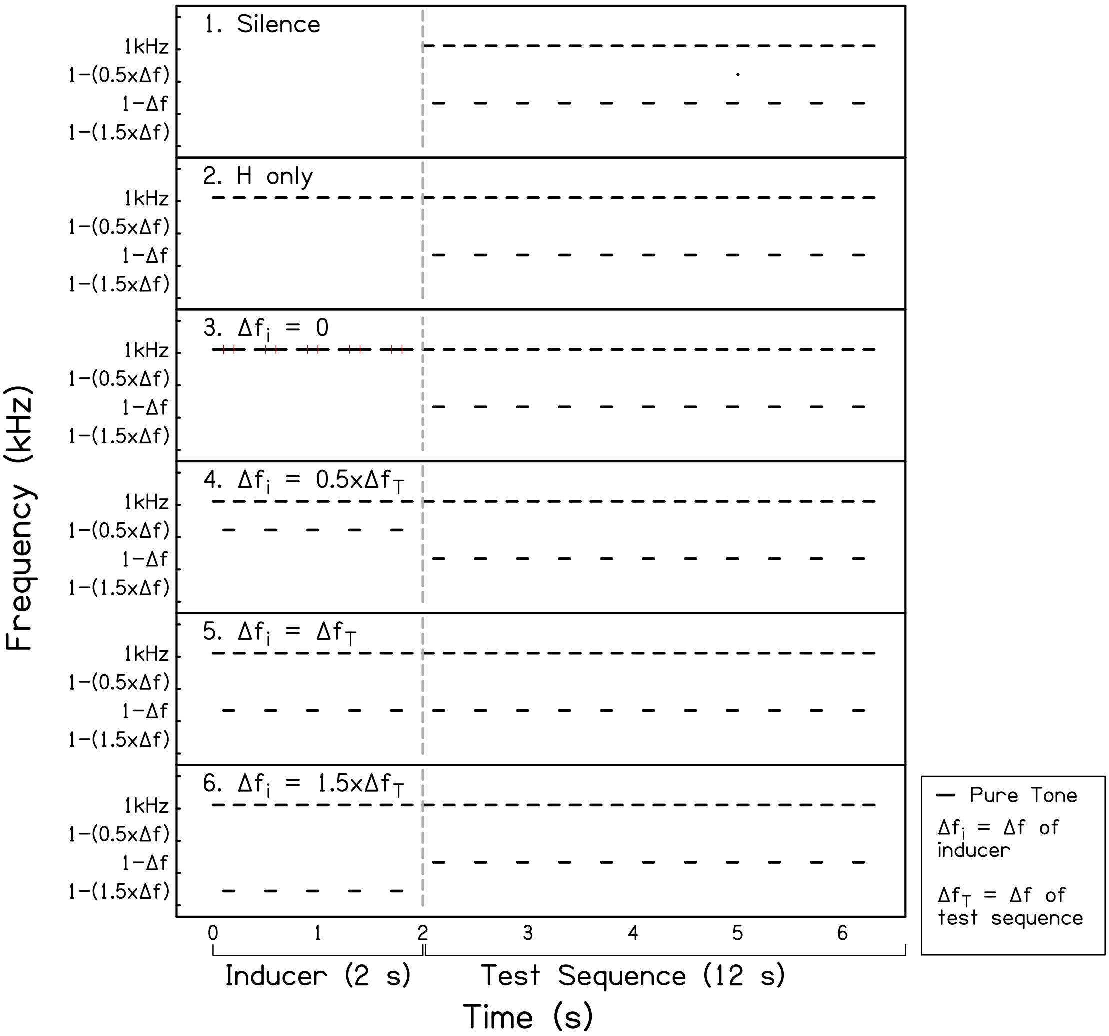

FIGURE 6.5: Illustration of the conditions (1-6) used in Experiment 8.

(pairwise comparisons for Δf_{AB} and Time interval are summarised in the Appendix Tables A.23 andA.24).

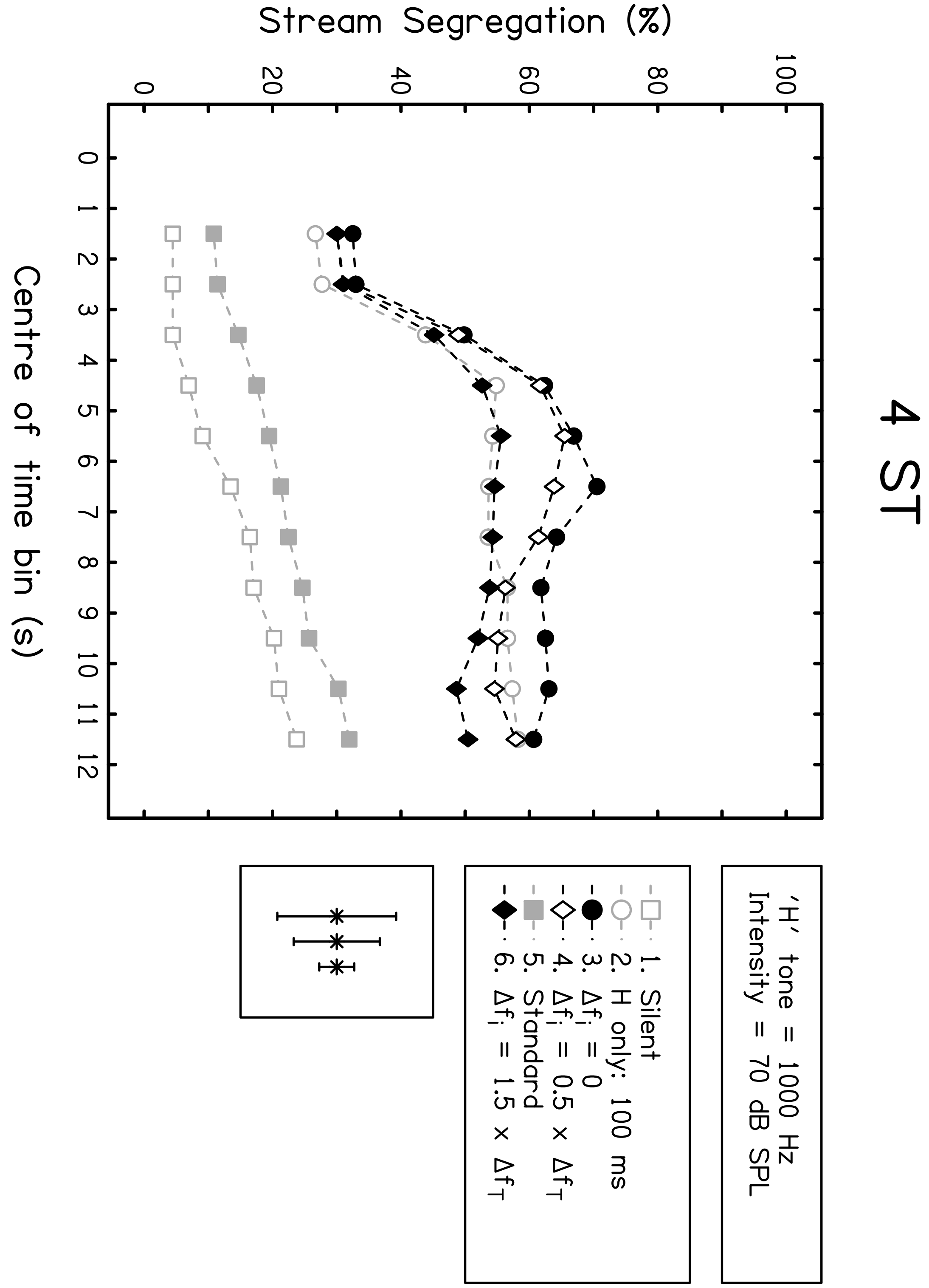

FIGURE 6.6: The stream segregation data averaged across listeners from Experiment 8, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

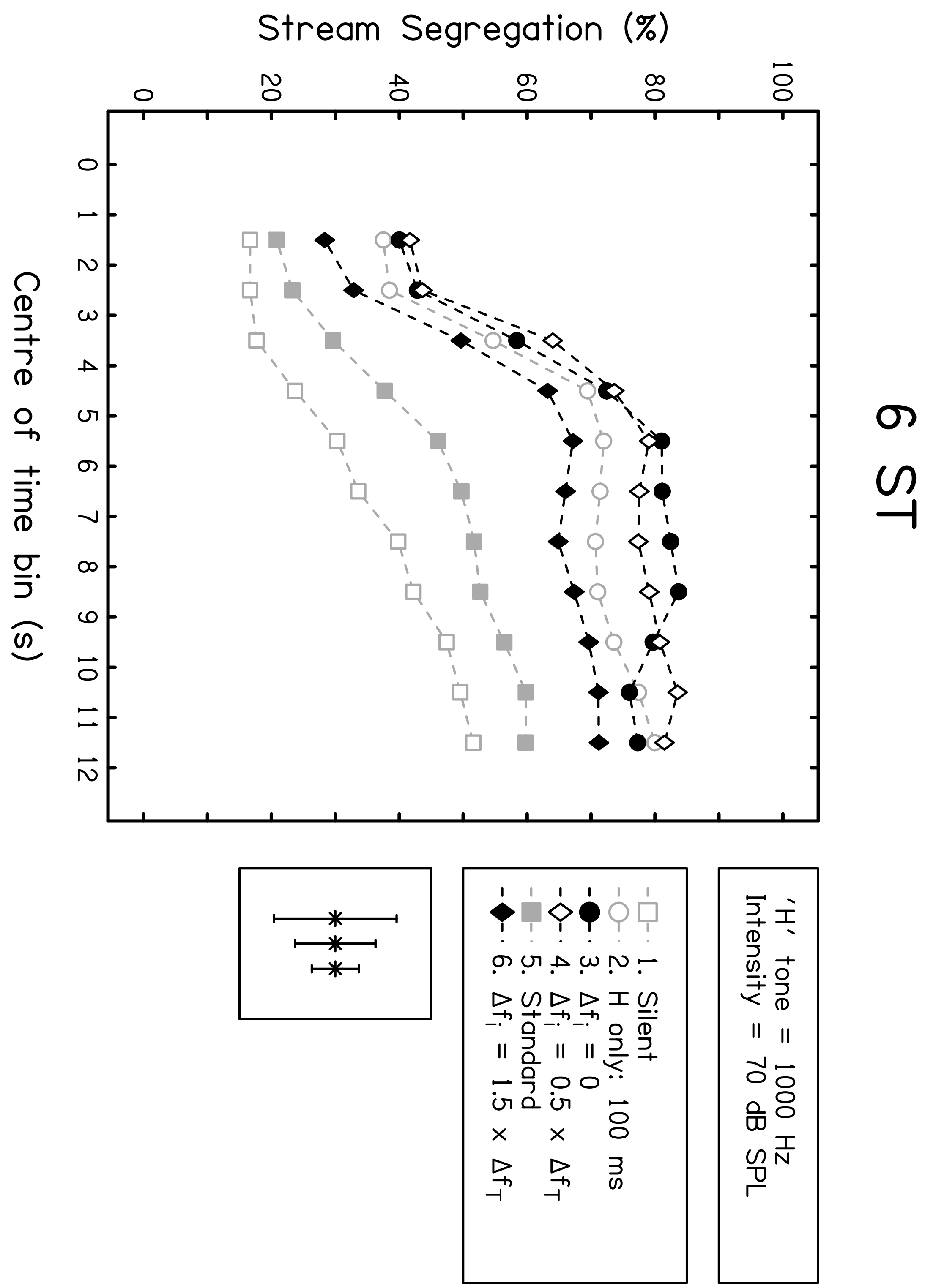

Figure 6.7: The stream segregation data averaged across listeners from Experiment 8, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

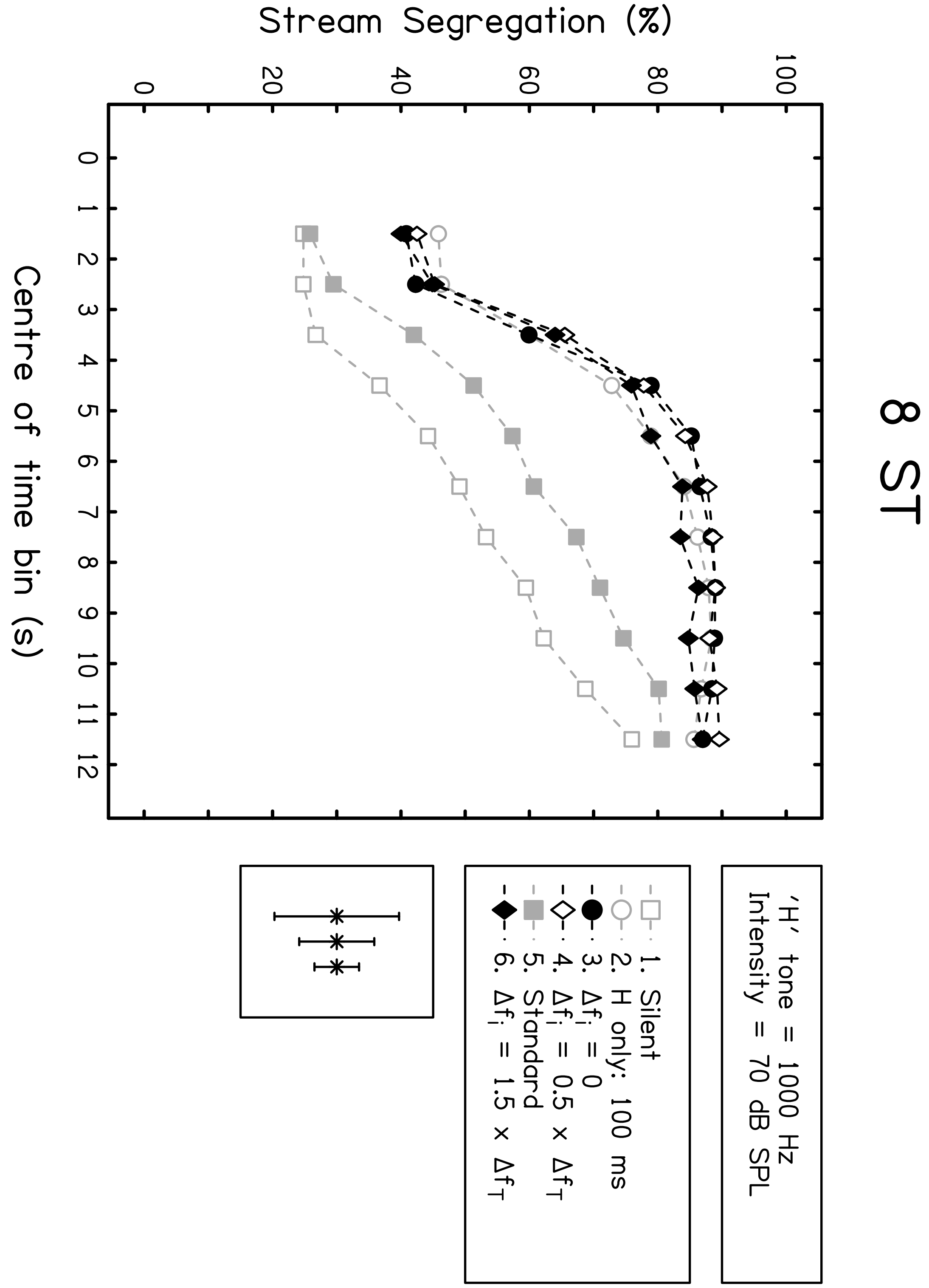

FIGURE 6.8: The stream segregation data averaged across listeners from Experiment 8, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

TABLE 6.11: Three-way repeated measures ANOVA comparing all conditions

Factor	*df*	*F*	*p*	*p2*
Δf_{AB}	**(2,22)**	**47.821**	**<0.001**	**0.813**
Condition	**(5,55)**	**38.262**	**<0.001**	**0.777**
Time Interval	**(10,110)**	**42.890**	**<0.001**	**0.796**
Δf_{AB} x Condition	(10,110)	1.609	0.113	0.128
Δf_{AB} **x Time Interval**	**(20,220)**	**8.843**	**<0.001**	**0.446**
Condition x Time Interval	**(50,550)**	**2.640**	**<0.001**	**0.194**
Δf_{AB} x Condition x Time Interval	(100,1100)	0.708	0.986	0.060

TABLE 6.12: Pairwise Comparison of condition across frequency separation and time.

(I) Condition	(J) Condition	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	**-31.7**	**4.1**	**<0.001**
	3	**-36.4**	**4.0**	**<0.001**
	4	**-35.7**	**4.7**	**<0.001**
	5	**-9.8**	**2.4**	**0.002**
	6	**-29.0**	**4.2**	**<0.001**
2	**1**	**31.7**	**4.1**	**<0.001**
	3	-4.7	2.5	0.090
	4	-4.0	3.7	0.296
	5	**21.9**	**3.4**	**<0.001**
	6	2.7	1.7	0.147
3	**1**	**36.4**	**4.0**	**<0.001**
	2	4.7	2.5	0.090
	4	0.7	3.8	0.863
	5	**26.7**	**3.4**	**<0.001**
	6	**7.4**	**1.9**	**0.002**
4	**1**	**35.7**	**4.7**	**<0.001**
	2	4.0	3.7	0.296
	3	-0.7	3.8	0.863
	5	**26.0**	**3.9**	**<0.001**
	6	6.7	3.4	0.079
5	**1**	**9.8**	2.4	**0.002**
	2	**-21.9**	**3.4**	**<0.001**
	3	**-26.7**	**3.4**	**<0.001**
	4	**-26.0**	**4.0**	**<0.001**
	6	**-19.3**	**3.3**	**<0.001**
6	**1**	**29.0**	**4.2**	**<0.001**
	2	-2.7	1.7	0.147
	3	**-7.4**	**1.9**	**0.002**
	4	-6.7	3.5	0.079
	5	**19.3**	**3.3**	**<0.001**

6.3.3.1 Δf_{AB} and Time Interval

The expected pattern of build-up and faster rate of build-up with larger Δf_{ABs} was shown in the significant main effects for Δf_{ABs}, Condition and Time Interval and the interaction term Δf_{ABs} × Time Interval ($p < 0.001$, Table 6.11). Consistent with this, the curves for conditions tended be highly segregated and converge beyond the 10-s time-point (as shown in Figures 6.2 to 6.4).

6.3.3.2 Condition

The silent inducer produced a significantly lower extent of segregation in comparison with all other conditions (mean differences = 9.8 to 36.4 percentage points, $p < 0.002$, Table 6.12). The standard inducer case ($\Delta f_i = \Delta f_t$, Condition 5), which could be considered a time-shifted version of the silent case, was on average 9.8 percentage points more segregated than the silent inducer case, but it remained significantly lower than all the Δf shift conditions (mean differences = 21.9 to 26.7 percentage points, $p < 0.001$, Table 6.12).

Although a consistent pattern emerged of the $\Delta f_i = 0$ case (or repeating high frequency tones) inducing the highest extent of segregation, followed by the $0.5 \times \Delta f_t$, H-only and $1.5 \times \Delta f_t$ inducers, the differences between these cases were not significant (Table 6.12). In addition, the heightened segregation level achieved by the constant frequency (H only case) did not differ from that achieved by the three Δf-shift conditions ($p > 0.05$, Table 6.12). This may be due to the greater extent of segregation induced at 8 ST, which limited differentiation of these cases at the greatest Δf_{ABs} (see Table 6.6 vs. Tables 6.8 and 6.7).

The faster rates of build-up for the H-only and Δf-shift cases were indicated by the significant interaction between Condition and Time Interval ($p < 0.001$, Table 6.11). The patterns of build-up for all conditions were maintained across Δf_{AB}, shown in the failure of the three-way interaction to reach significance Δf_{AB} × Condition × Time Interval ($p = 0.986$, Table 6.11).

6.3.4 Discussion

Consistent with Experiment 7, the 'H-H-' inducer promoted a highly segregated perception of the test sequency, perhaps through capture of the corresponding 'H' tone subset of the test sequence (c.f. Bregman and Rudincky, 1975; Beauvois and Meddis, 1997; Rogers and Bregman, 1998; Roberts, Glasberg, and Moore, 2008; Haywood and Roberts 2010, 2011, 2013). Contrary to the findings of Rogers and Bregman, (1993), the greatest segregation of test sequences was induced when $\Delta f_i = 0$ (i.e. 'HHH-' inducer). This most likely arose from the increased tone density, number of onsets/offsets or high presentation rate. Unlike the comparable 4 tones/cycle inducer case used by Rogers and Bregman, (1993), this 'HHH-' case maintained the same rhythm as the 'HLH-' case, and so the outcome is consistent with the assertion than rhythmic similarity is required for effective stream biasing (Snyder and Weintraub, 2011).

The results of this study contrast with the established finding of Snyder at al. (2008, 2009), that a larger Δf for a prior sequence lessens the segregated percept of the following sequence. The main outcome of this experiment was that changing Δf_i in either direction increases segregation. This is clearly different from the contrastive effect of change (smaller-to-larger or v/v) in the Snyder studies.

In both cases where the 'L' tones were moved at the inducer-test boundary—either away from or closer to the 'H' tones—the test sequence was perceived as highly segregated. This discrepancy between studies can be explained by key differences in the test paradigm. Snyder at al. (2008, 2009) always presented (or retrospectively analysed) sequences separated by a silent interval during which listeners were instructed not to record their responses, indicating that both sequences were discrete. In this study, whilst the inducer-test boundary was cued by a change in the instructions visually presented to listeners, the absence of a silent interval is likely to have indicated that both the inducer and test sequence were two parts of a single longer sequence. The continuous nature of a single trial, including preservation of the inter-stimulus intervals, could have permitted capture of the 'H' tones out of the test sequence. This would indicate that in the case of continuous sequences, the effect of a constant frequency inducer is a result of 'perceptual capture' rather than the slow adaptation model suggested by Snyder at al. (2009).

In summary, changing the frequency of the 'L' tone between inducer and test sequence enhances the perception of segregation for the subsequent test sequence, with some evidence of a trend towards a level exceeding that elicited by a constant frequency ('H-H-') inducer. This effect is lessened when the 'L' tone moves to a frequency region closer to that of the 'H' tone. Additionally, the inducer defined by $\Delta f_i = 0$ shows that simply preserving the rhythm of the sequence is not sufficient to preserve a rate of build-up matching the standard sequence; rather, increasing the number of high frequency tones in the inducer enhances the extent of segregation in the test sequence.

6.4 Experiment 9: Accompanying the induction sequence with a harmonic captor complex

Continuing on from the previous two experiments, which achieved segregation-promotion by independently varying the level or frequency of one tone subsets, Experiment 9 used a synchronous harmonic complex to attempt 'capture' of the 'L' subset of tones in a 'HLH-' sequence. A complex of 3 tones (250, 500, and 750 Hz) was aligned with the 'L' tone set at 1 kHz which if effectively 'captured' would be heard as the 4th harmonic of the complex. As for Experiment 8, a 2-s inducer was followed by the 12-s 'HLH-' test sequence (5 + 30 triplets) presented binaurally at 70 dB SPL. Δf_{AB} was set at 4-, 6-, and 8-ST.

6.4.1 Conditions and Hypotheses

The induction and accompanying sequences used were as follows:

1. *Silence*
2. *Standard:* 'HLH-' inducer, identical to the test sequence.
3. *H-only:* Segregation-promoting 'H-H-' inducer, high tones only, low tones replaced by silence of equal duration.
4. *Standard + Sync:* 'HLH-' inducer accompanied by a harmonic complex of 250, 500, and 750 Hz simultaneous with the 'L' tone.

5. *Standard + Advanced Async:* 'HLH-' inducer accompanied by a harmonic complex of 250, 500, and 750 Hz, but advanced by 200 ms relative to the onset of the 'L' tone. Hence, the first harmonic complex is presented prior to the first triplet, and the next four complexes are simultaneous with the silent interval. This arrangement ensures that the final silent interval of the inducer is maintained.

6. *Standard + Delayed Async:* 'HLH-' inducer accompanied by a harmonic complex of 250, 500, and 750 Hz, but delayed by 200 ms relative to the onset of the 'L' tone. Hence, the first harmonic complex is presented during the silent interval subsequent to the first triplet to the first H tone, and the next four complexes are simultaneous with the silent interval. This means that the final silent interval of the inducer, at the inducer-test boundary, is accompanied the harmonic complex.

7. *Sync only:* Only the repeating harmonic complex occurring at the times when the 'L' tone would occur in the standard sequence.

8. *Async (advanced) only:* Only the repeatingharmonic complex, but advanced by 200 ms from the time point that the 'L' tone would otherwise occur.

9. *Async (delayed) only:* Only the repeating harmonic complex, but delayed by 200 ms from the time point that the 'L' tone would otherwise occur.

It was predicted that the harmonic relationship of the 'L' tone with the synchronous complex would lead to fusion of the lower subset of the inducer tones with the harmonic complex, effectively lowering the centre frequency of the 'L' tone complex and changing its timbral quality. In light of the results from Experiments 7 and 8, increasing the frequency separation and timbral difference between the tone subsets should facilitate the perceptual isolation of the unmanipulated 'H' tones in the inducer, leading to the sequential capture of the corresponding subset in the test sequence.

6.4.2 Participants and Procedure

Twelve normal-hearing listeners took part in this experiment. As described in Chapter 2, all conditions were presented during each of the 10 blocks over two sessions (5 blocks in each session).

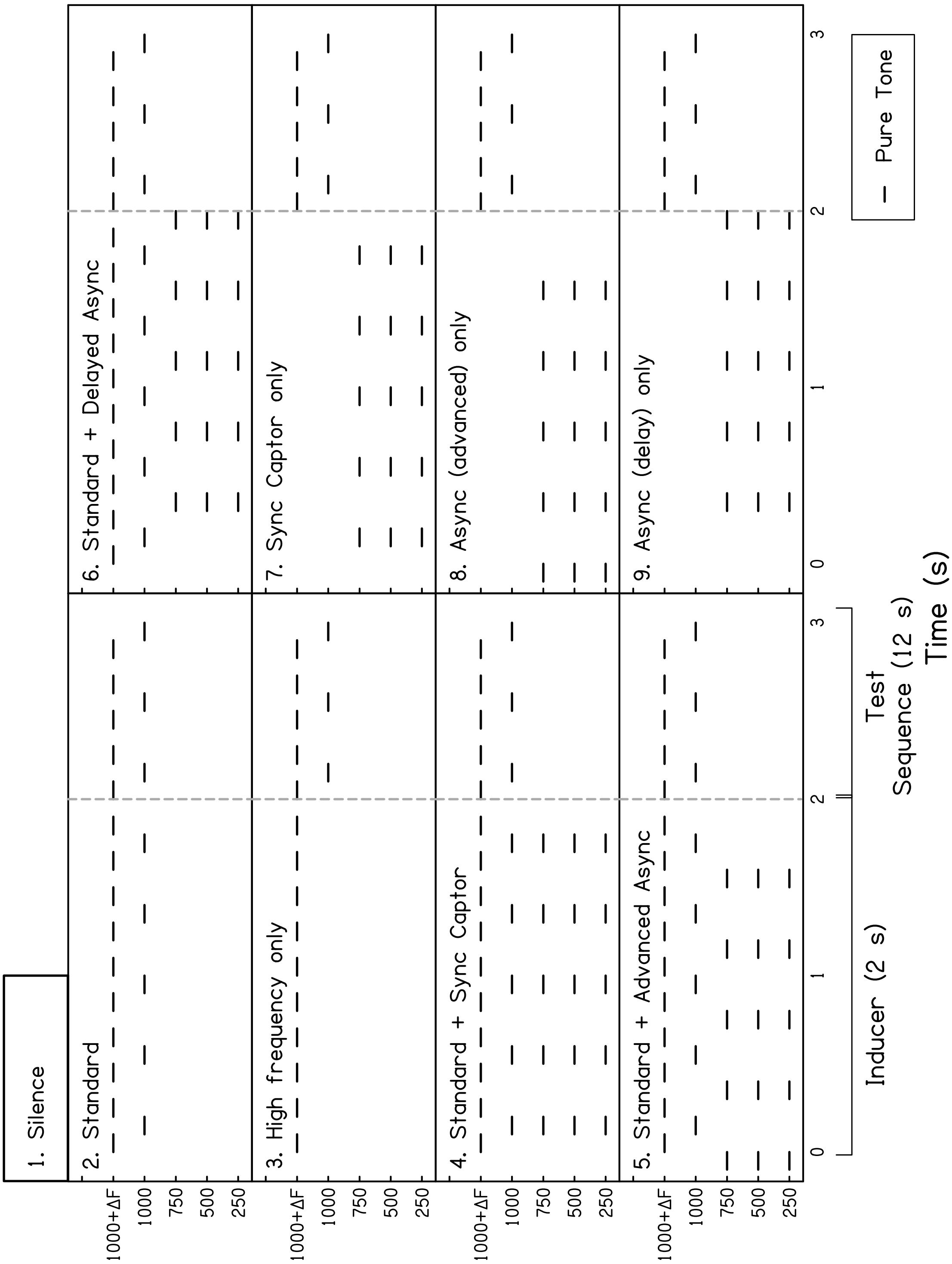

FIGURE 6.9: Illustration of the conditions (1-9) used in Experiment 9.

TABLE 6.13: Three-way repeated measures ANOVA comparing all conditions

Factor	*df*	*F*	*p*	*p2*
Δf_{AB}	**(2,22)**	**50.407**	**<0.001**	**0.821**
Condition	**(8,88)**	**28.245**	**<0.001**	**0.720**
Time Interval	**(10,110)**	**70.783**	**<0.001**	**0.865**
Δf_{AB} **x Condition**	**(2,22)**	**2.284**	**0.005**	**0.172**
Δf_{AB} **x Time Interval**	**(16,176)**	**17.488**	**<0.001**	**0.614**
Condition x Time Interval	**(120,220)**	**7.940**	**<0.001**	**0.419**
Δf_{AB} **x Condition x Time Interval**	**(80,880)**	**1.532**	**<0.001**	**0.122**

6.4.3 Results

As for Experiment 8, a single three-way repeated measures ANOVA was run on all conditions over the 11 time intervals (Table 6.13). The results are shown for each Δf_{AB} in Figures 6.10-6.12. Both panels display the reference cases in grey (silent, standard, and segregation-promoting inducers). Overlaying the references cases in the left panel, are the cases where the harmonic complex accompanies the standard induction sequence (both synchronous and asynchronous with the 'L' base tone). In the right-hand panel, the references cases are shown with the conditions where the inducer consists of only the harmonic complex (without the accompanying standard alternating 'HLH-' triplets).

6.4.3.1 Δf_{AB} and Time Interval

The anticipated build-up and elevated rates of build-up could be observed for all conditions, although it was lessened for the repeating H-tone inducer. The influence of Δf_{AB} and Time Interval were apparent in the significant main effects of these two conditions and in the interaction term $\Delta f_{AB} \times$ Time Interval ($p < 0.001$, Table 6.13). The highly differentiated patterns of build-up for each condition and limited influence of Δf_{AB} on the rate of build-up for the H-only case was shown in the significant three-way interaction $\Delta f_{AB} \times$ Condition $\times$ Time Interval ($p < 0.001$, Table 6.13).

6.4.3.2 Addition of a harmonic complex to the inducer

Overall, the repeating H-tone inducer promoted the most segregated perception of the test sequence, substantially elevated in comparison with all other cases including the

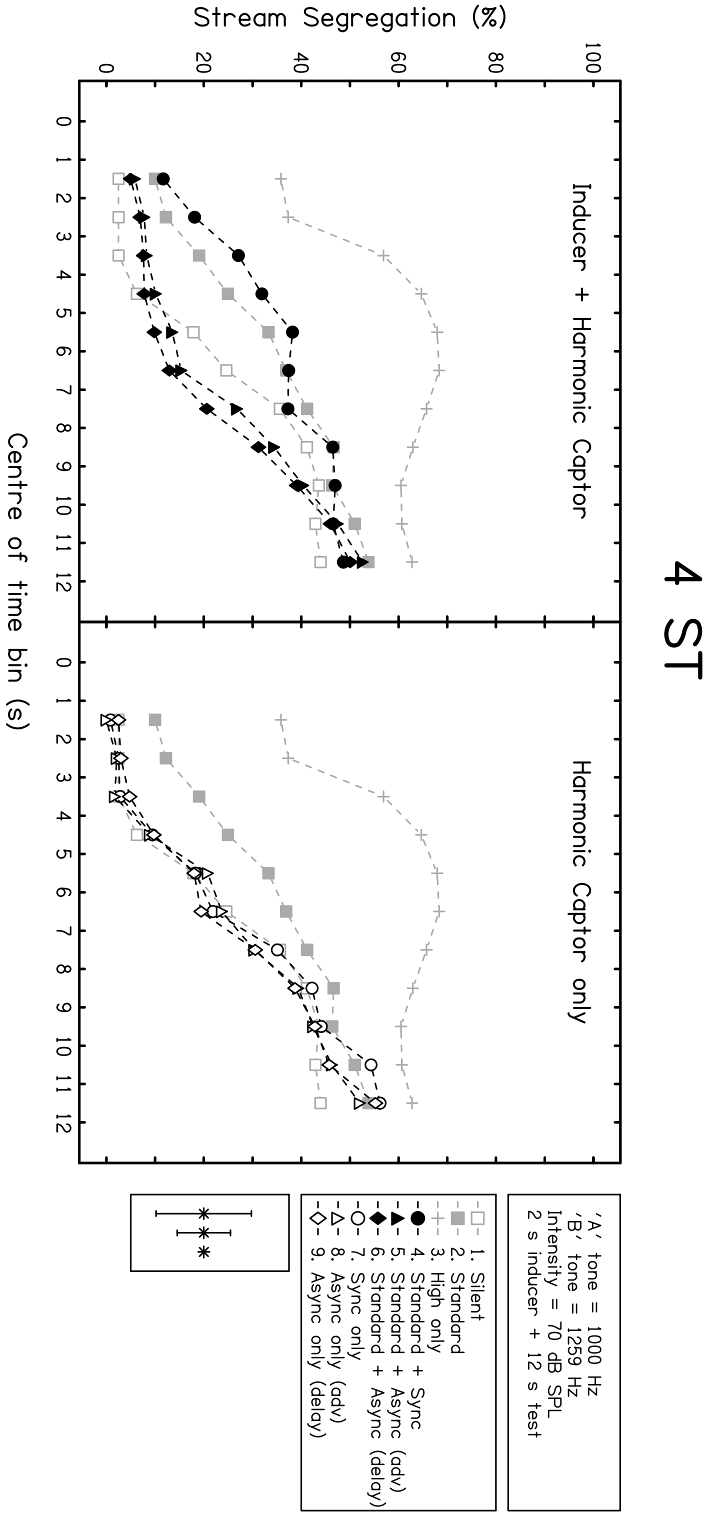

Figure 6.10: The stream segregation data averaged across listeners from Experiment 9, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 4 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

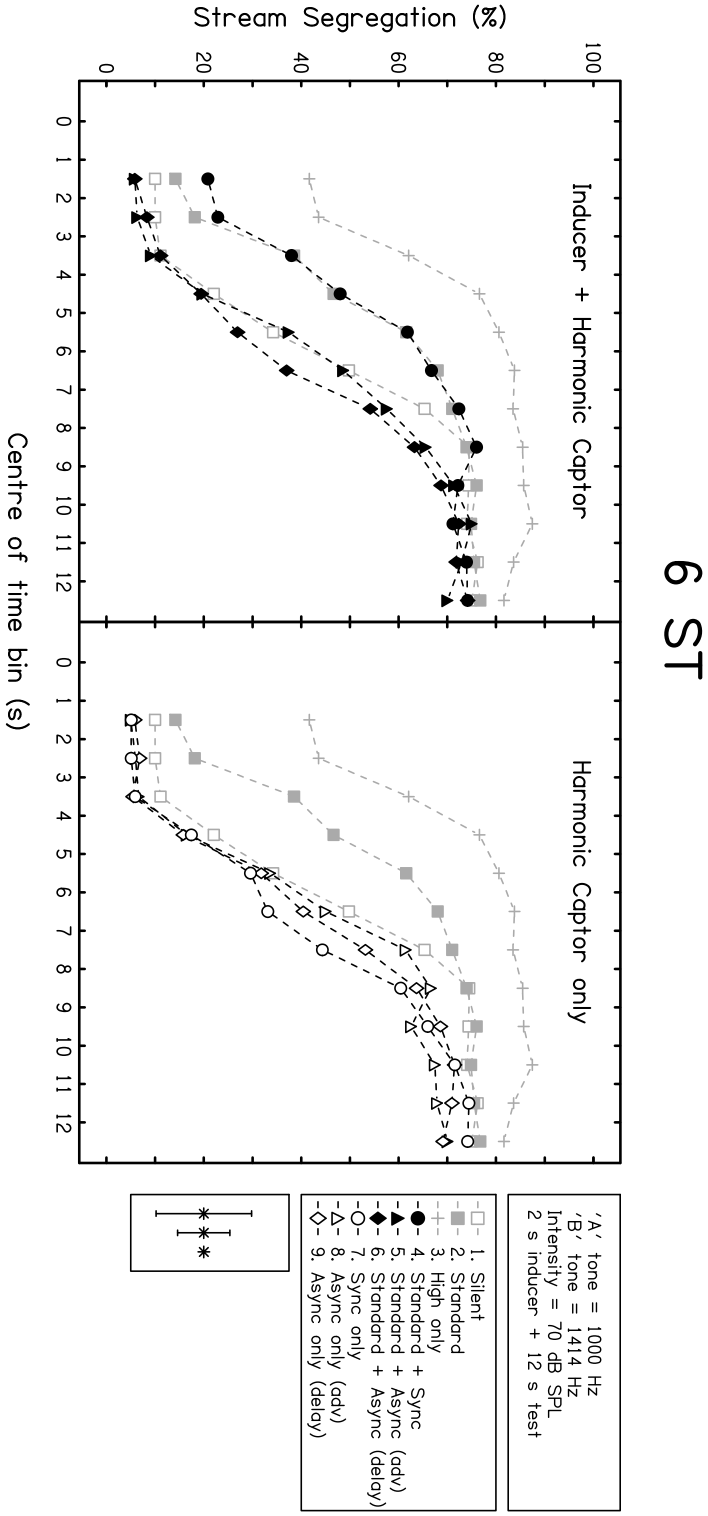

Figure 6.11: The stream segregation data averaged across listeners from Experiment 9, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 6 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

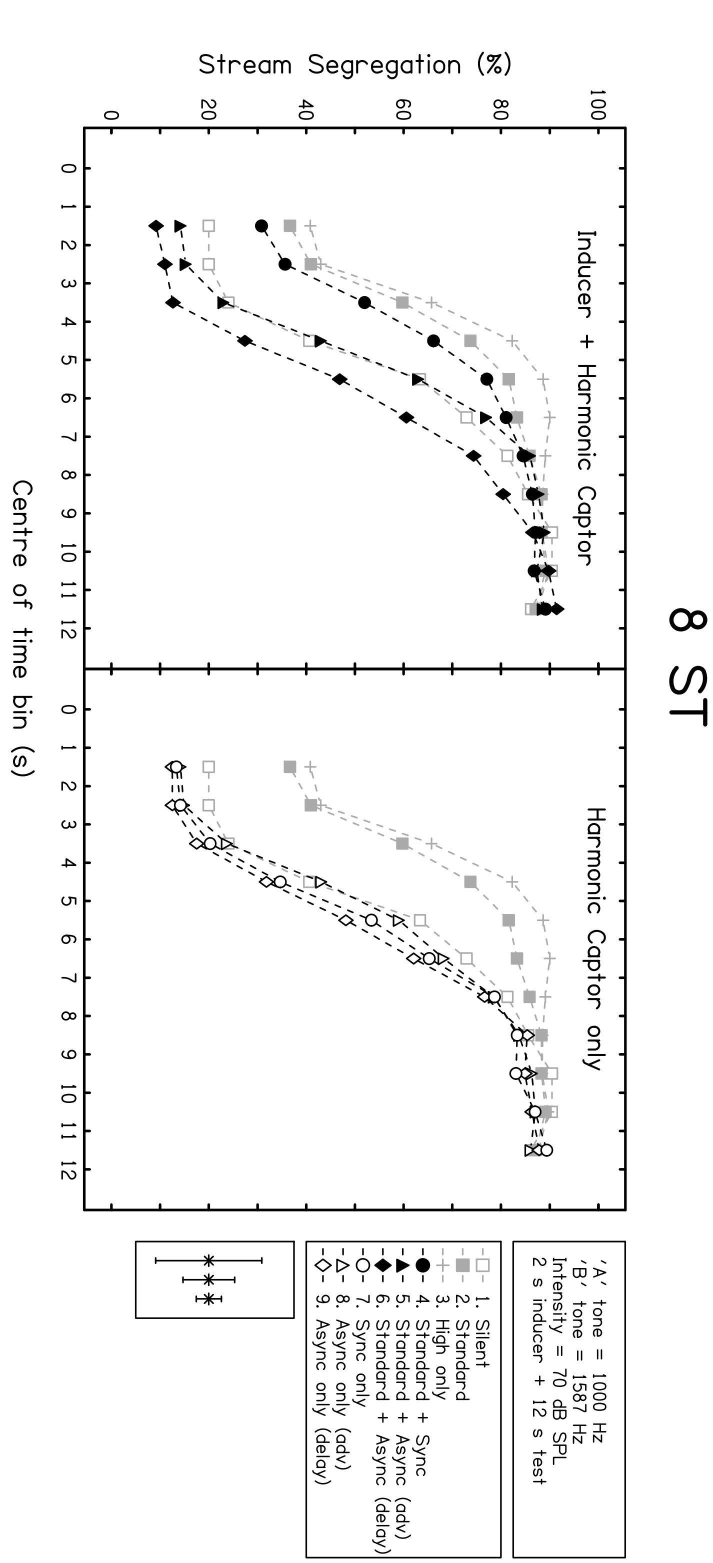

Figure 6.12: The stream segregation data averaged across listeners from Experiment 9, displaying the pattern of build-up over the 12-s test sequence (following a 2-s inducer) for a Δf_{AB} of 8 ST. The insert identifies the test conditions and the 3 error bars show the maximum, mean, and minimum standard error across condition.

Table 6.14: Pairwise Comparison of condition across frequency separation and time - conditions 1-5 compared with all others.

(I) Condition	(J) Condition	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	**-11.17**	**1.26**	**<0.001**
	3	**-26.41**	**3.09**	**<0.001**
	4	**-10.63**	**3.16**	**0.006**
	5	1.04	2.59	0.695
	6	5.28	2.83	0.089
	7	2.09	2.35	0.391
	8	**4.02**	**1.74**	**0.041**
	9	**4.06**	**1.68**	**0.034**
2	**1**	**11.17**	**1.26**	**<0.001**
	3	**-15.24**	**3.12**	**<0.001**
	4	0.53	3.11	0.867
	5	**12.21**	**2.18**	**<0.001**
	6	**16.44**	**2.84**	**<0.001**
	7	**13.26**	**1.53**	**<0.001**
	8	**15.19**	**1.42**	**<0.001**
	9	**15.23**	**1.38**	**<0.001**
3	**1**	**26.41**	**3.09**	**<0.001**
	2	**15.24**	**3.12**	**<0.001**
	4	**15.77**	**2.13**	**<0.001**
	5	**27.45**	**3.86**	**<0.001**
	6	**31.68**	**4.08**	**<0.001**
	7	**28.50**	**3.20**	**<0.001**
	8	**30.43**	**3.49**	**<0.001**
	9	**30.47**	**3.46**	**<0.001**
4	**1**	**10.63**	**3.16**	**0.006**
	2	-0.53	3.11	0.867
	3	**-15.77**	**2.13**	**<0.001**
	5	**11.68**	**3.82**	**0.011**
	6	**15.91**	**4.27**	**0.003**
	7	**12.73**	**2.96**	**0.001**
	8	**14.66**	**3.46**	**0.001**
	9	**14.70**	**3.56**	**0.002**
5	1	-1.04	2.59	0.695
	2	**-12.21**	**2.18**	**<0.001**
	3	**-27.45**	**3.86**	**<0.001**
	4	**-11.68**	**3.82**	**0.011**
	6	4.24	2.01	0.059
	7	1.05	2.14	0.634
	8	2.98	3.20	0.372
	9	3.02	2.23	0.203

Table 6.15: Pairwise Comparison of condition across frequency separation and time - conditions 6-9 compared with all others.

(I) Condition	(J) Condition	Mean Difference [I-J] (%)	Std. Error (%)	*p*
6	1	-5.28	2.83	0.089
	2	**-16.44**	**2.84**	**<0.001**
	3	**-31.68**	**4.08**	**<0.001**
	4	**-15.91**	**4.27**	**0.003**
	5	-4.24	2.01	0.059
	7	-3.18	3.11	0.328
	8	-1.26	3.58	0.732
	9	-1.21	2.46	0.631
7	1	-2.09	2.35	0.391
	2	**-13.26**	**1.53**	**<0.001**
	3	**-28.50**	**3.20**	**<0.001**
	4	**-12.73**	**2.96**	**0.001**
	5	-1.05	2.14	0.634
	6	3.18	3.11	0.328
	8	1.93	1.97	0.348
	9	1.97	1.63	0.251
8	**1**	**-4.02**	**1.74**	**0.041**
	2	**-15.19**	**1.42**	**<0.001**
	3	**-30.43**	**3.49**	**<0.001**
	4	**-14.66**	**3.46**	**0.001**
	5	-2.98	3.20	0.372
	6	1.26	3.58	0.732
	7	-1.93	1.97	0.348
	9	0.04	1.50	0.978
9	**1**	**-4.06**	**1.68**	**0.034**
	2	**-15.23**	**1.38**	**<0.001**
	3	**-30.47**	**3.46**	**<0.001**
	4	**-14.70**	**3.56**	**0.002**
	5	-3.02	2.23	0.203
	6	1.21	2.46	0.631
	7	-1.97	1.63	0.251

standard case, where the inducer was the same as the test sequence (mean difference ranged between 15.2 to 31.8 percentage points, $p < 0.001$, Table 6.14). This case also produced a highly rapid initial rate of build-up in comparison with all other cases, accounting for the significant Condition × Time Interval ($p < 0.001$, Table 6.13). The silent inducer produced a more integrated percept of the test sequence than the standard case, but the pattern of build-up remained the same (mean difference = -11.2 percentage points, $p < 0.001$, Table 6.14).

The main effect of condition, whilst driven to some extent by the significant differences between the silent, standard and H-only inducer cases also reflected other differences in the profiles of segregation ($p < 0.001$, Table 6.13) including the addition of a harmonic complex to the standard 'HLH-' inducer (see the right-hand panels of Figures 6.10-6.12). The standard + synchronous inducer produced a comparable pattern of build-up and overall extent of segregation as the standard only case (the mean difference of 0.53 percentage points was not significant, $p = 0.867$, 6.14). Both standard + asynchronous inducer cases promoted a significantly more integrated perception of the test sequence (mean difference = -12.2 to -16.4 percentage points $p < 0.001$, Table 6.13) comparable with the silent case ($p > 0.05$, 6.14).

6.4.3.3 Harmonic complex only inducers

The same pattern as the silent inducer case was also observed for all three of the harmonic complex only inducers (see the right-hand panels of Figures 6.10-6.12). The synchronous harmonic complex showed approximately the same profile of segregation as the silent case, with no significant difference ($p > 0.05$, 6.14). Whilst both of the asynchronous harmonic complex inducers produced similar patterns as the silent case, with small but significantly higher extents of segregation (mean difference = 4.0 to 4.1 percentage points, $p < 0.05$, 6.14).

6.4.4 Discussion

In contrast with the Experiments 7 and 8, segregation promotion of the test sequence only occurred for the H-only inducer (condition 3). Whilst the pattern for the silent, standard, and H-only inducer replicated that of the earlier experiments reported here, and of Haywood and Roberts (2013), the expected isolation of the H tones in the standard+sync inducer—through presentation of the L tones with a synchronous harmonic complex—did not occur. Informal listening revealed that presentation of the synchronous complex with the standard sequence resulted in timbral fusion of the 'L' tones with the complex, and so it would appear that the expected fusion did occur. Whilst this acted to lower the centre of gravity of the fused L-tone complex, it nonetheless failed to isolate the lower frequency tone subset from the 'HLH-' sequence. It appears that maintaining the distance between the frequency of the H tone and the upper edge of the tone complex indicates that a single, alternating, induction sequence is being presented.

It was anticipated that that the complex-only cases would induce a similar percept to the silent case (i.e., no induction), and this is what was observed. What was not expected was the effect of accompanying the standard induction sequence with the captor complex. First, the segregation induced by the standard+sync case was very similar to that induced by the standard case alone. Second, accompanying the standard inducer with either of the asynchronous captor complexes resulted in a subsequent percept at least as integrated as that for the silent-inducer case. Although not statistically significant, there are signs of a trend indicating that the delayed case had the strongest inhibitory effect on build-up. A possible explanation for these findings is that the presence of a harmonic complex during the silent intervals of the 'HLH-' sequence disrupted the rhythm by introducing a 'double gallop' percept, biasing the auditory system towards a more integrated percept of the subsequent test sequence. This kind of effect may have been stronger for the delayed case as the final harmonic complex was presented during the silent interval directly preceding the test sequence, thereby extending the disruption of rhythm to the first test triplet. This result is consistent with the effect of a manipulation used to disguise the gallop used by Rogers and Bregman (1993). In that disguised case, 'distractor' tones were presented in the non-test ear to disrupt the rhythm of the test tones presented in the contralateral ear. The disguised gallop condition induced a similar level of segregation to the control case of white noise presented bilaterally.

6.5 General Discussion

Experiments 7 and 8 explored stream biasing by manipulating the level and frequency differences between the tone subsets in an induction sequence to explore the capturing out of tone subsets from the subsequent test sequence. Experiment 9 attempted segregation promotion using a tone complex that was harmonically related to, and synchronous with, the lower-frequency tone subset of the test sequence. These experiments demonstrated that segregation promotion of either tone subset can be achieved by adjusting the perceptual space (in frequency or level) between the inducer tone subsets, and these effects persisted throughout the course of a 12-20-s test sequence. The ability of both the smaller and larger frequency separations in the inducer (Experiment 8) to promote segregation of the test sequence tones, suggests that the direction of the level change may not have been critical to the outcome of Experiment 7. It seems that segregation promotion is most effective when a single tone subset changes at the inducer-test boundary, whilst the other subset remains unchanged.

The ability of an additional complex to promote a segregated percept was shown in Experiment 9 to be limited by the degree to which it fuses with the target tones. Although a synchronous and harmonically related tone complex may well have fused with the synchronous subset, that did not lead to segregation of the A and B subsets in the short inducer, and so the sequence rhythm was maintained?

Additionally, the constant difference between the upper bound of the complex and the higher tone across the inducer-test boundary was sufficient to maintain build-up of segregation in line with a standard alternating case. As noted by Rogers and Bregman (1993) and Snyder and Weintraub (2011), keeping the rhythm regular was a key feature in promoting segregation or build-up. In cases where rhythm was kept constant, even when the frequency of both subsets was made the same (i.e. the frequency separation was zero, as for Experiment 8), the intial segregation level was high and remained high throughout the test sequence. Addition of an asynchronous tone complex which filled the silent intervals (between triplets) of the alternating sequence was sufficient to disrupt the standard pattern of build-up, perhaps due to the ‘disguise’ of the ‘gallop’ rhythm.

Considered together, the persistence of the segregation promoting effect across all cases, and the influence of rhythm on the extent of this effect, is consistent with a perceptual capture account of segregation promotion (Rogers and Bregman, 1993; Haywood and Roberts, 2013). The discrepancy between the results obtained here and the observations of Snyder et al. (2008, 2009a, 2009b, 2011), are most likely a result of the differences between the test paradigms. The silent interval separating trials in these earlier studies may have encouraged listeners to contrast the two trials. In fact, the opposing segregation/ integration promoting effect of transitioning from sequences with a smaller frequency separation to those with a larger separation, and vice versa, is suggestive of the patterns of resetting and overshoot observed in the earlier experiments of this thesis.

In the studies presented in this chapter, and by Rogers and Bregman (1993) and Haywood and Roberts (2013), there was no auditory cue between the inducer and test sequence, aside from the change in sequence properties. Listeners were therefore more inclined to attend to the sequence of tones that remained unchanged over the duration of the test boundary. The effects observed in this chapter are accordingly more likely to be a result of comparisons in perceptual similarity rather than a consequence of the slower neural adaptation of frequency specific neurons.

In conclusion, the experiments presented in this chapter have demonstrated that segregation promotion can be achieved by independently varying the properties of one tone subset in an inducer. Addition of a harmonic complex to a standard inducer, whilst changing the perceptual quality of the sequence, does not necessarily successfully promote capture. However an asynchronous complex can prevent the build-up of stream segregation, potentially by disrupting the characteristic 'galloping' rhythm of the inducer sequence.

Chapter 7

General Discussion

7.1 Introduction

The nine experiments presented within this thesis examined the effect of changes in sequence properties on the dynamics of stream segregation. A sequence consisting of alternating low and high frequency pure tones can be perceived in two alternative ways. First, as a single, integrated stream with a characteristic galloping rhythm, for which the pitch of the tones is heard to move from low to high and vice versa. Second, as two segregated streams, one repeating sequence of high frequency tones and another sequence of low frequency tones. For intermediate frequency separations and tone repetition rates, the dominant percept is also influenced by attentional set (Miller and Heise, 1950; van Noorden, 1975). For sequences with a fixed repetition rate and frequency separation, the tendency to perceive the tones as segregated increases with time (van Noorden, 1975; Bregman, 1978; Anstis and Saida, 1985). Initially, there tends to be a rapid increase in segregation level (for up to 10 s), followed by a slower increase that can continue at least up to a minute (Anstis and Saida, 1985). This build-up can be reset on presentation of an abrupt change within an ongoing sequence, causing a rapid fall in the extent of segregation (Rogers and Bregman, 1993, 1998; Roberts et al., 2008; Haywood and Roberts, 2010, 2013).

Two different accounts of the mechanism underlying build-up have been proposed. Bregman (1978) considered build-up to arise from an evidence accumulation process; he suggested that the auditory system requires time to build-up evidence before interpreting a single auditory input as being produced by two distinct and independent sources. An abrupt change could therefore signal a new sound event, restarting the evidence-accumulation process and returning to the single-percept bias. A plausible neural basis for this process is the multi-second neural adaptation model (Micheyl et al., 2005; Pressnitzer et al., 2008). According to this model, build-up is a by-product of the decay in the response magnitude of neural responses, as observed in the primary auditory cortex of rhesus macaques (Micheyl et al., 2005) and the cochlear nucleus of guinea pigs (Pressnitzer et al., 2008). In both cases, these authors noted a habituation of neural responses following a similar time-course to the build-up observed from human psychophysical data. This habituation results from a long-term synaptic depression and fast recovery of peripheral neurons. In accordance with this neural account of build-up, abrupt changes that stimulate different neural populations could re-set this process.

The perception of an alternating-frequency sequence can also be influenced by a preceding inducer sequence. An inducer comprising a repeating sequence of constant-frequency tones increases stream segregation of the subsequent test sequence by capturing out the corresponding subset of tones in the test sequence (Bregman and Rudnicky, 1975; Rogers and Bregman, 1993; Beauvois and Meddis, 1997; Roberts et al., 2008). This effect was demonstrated to be different to the build-up induced by an alternating frequency sequence; constant-frequency inducers cause a near instantaneous and substantially higher segregation level in comparison with an alternating sequence of the same length (Haywood and Roberts, 2013).

The experiments presented within this thesis used subjective methods to explore further the effect of changing stimulus properties on the dynamics of streaming. The aim was to extend our understanding of the time-course of sequential grouping by investigating the dynamics of stream segregation using stimuli somewhat closer to real-world stimuli by utilising test sequences with changing stimulus properties. The studies reported here were designed to address three general questions. The first was whether gradual changes, in addition to abrupt changes, can affect the dynamics of streaming within ongoing alternating-frequency sequences. The second was whether resetting occurs specifically as a result of correlated changes in stimulus properties of both tone subsets, and the third was whether stream capture or stream biasing can be achieved with the use inducers other than a single, repeating constant-frequency tone.

To avoid the complications of the effects of changes in excitation pattern, most of the experiments reported here used pure-tone sequences or variants that involved minimal changes in excitation pattern.

7.2 Summary and conclusions

7.2.1 The effect of gradual changes on streaming

Studies into the build-up of auditory stream segregation have generally used repeating sequences whose stimulus properties remain fixed for the duration of the sequence. These unchanging stimuli have little in common with those encountered in everyday listening environments. Rogers and Bregman (1998) explored the effect of gradual changes in level and lateralisation of an inducer sequence on the subsequent test sequence and found that both standard and gradual-change inducers exerted a similar influence on the test-sequence percept. The fixed test sequences that followed had the lowest segregation boundaries for these conditions, indicating that in both cases substantial build-up of segregation had occurred in response to the inducer. These results led Rogers and Bregman (1998) to suggest that these small, continuous changes were considered to be the gradual changing properties of sounds originating from a single source or resulted from the increasing overlap between regions sampled by the inducer and test sequence during the evidence accumulation process. However, the method used in their investigation required the listener to provide only a single, one-off judgement of the perception of the test sequence at the end of the trial. This provided limited information on the pattern of build-up during both the inducer and test sequences, whereas the approach used here provided [complete].

Using continuous monitoring of gradually changing sequences, Experiments 1 and 2 investigated whether the pattern of build-up remained the same for both constant and gradually varying alternating-frequency sequences with an LHL configuration. Properties that might be expected to vary within naturally occurring sounds base frequency and lateralisation (cued by ITD) were gradually changed in these two investigations. Experiment 2 used sequences of triplets that gradually drifted from one extreme lateralisation to the alternate lateralisation and back again in equal steps over 50 triplets (20-s long sequences). A similar pattern of build-up was observed for both the gradual and constant cases, consistent with the findings of Rogers and Bregman (1998) and lending weight to the argument that gradual changes cue a common source, preserving the ongoing evidence accumulation process.

The same approach in Experiment 1, demonstrated that the effect of gradual changes in base frequency was comparable to that of the fixed cases, demonstrating that even in cases where the excitation pattern is altered substantially over the course of a sequence, gradual change has a limited effect on the build-up of stream segregation. This could be because the similarity between the constant and gradual cases is maintained over time.

7.2.2 Resetting and overshoot caused by abrupt changes

Correlated abrupt changes within gradually drifting sequences Experiments 1 and 2 also explored the effect of abrupt changes within gradually varying sequences. In contrast with the fall in segregation level resulting from abrupt ITD changes observed by Rogers and Bregman (1998), the abrupt changes in lateralisation used in Experiment 2 exerted a limited effect on build-up despite the similar magnitude of these changes. There was no effect of an abrupt change for any A-B frequency separation, aside from the 6-ST case. This difference in outcomes between the two studies could be a result of the abrupt change occurring within a sequence that was already moving from one side to the other. The abrupt changes used by Rogers and Bregman (1998) only occurred at the inducer-test boundary.

Despite these weak effects of a single, abrupt change, multiple abrupt changes in lateralisation did exert influence on the build-up of streaming. Multiple abrupt changes in lateralisation, occurring every three triplets throughout the sequence, suppressed the overall extent of build-up. It is notable that these sequences did not incorporate any gradual shifts in ITD, as for the abrupt change cases in the Rogers and Bregman (1998) study, lending weight to the argument that continuously varying ITD diminishes the effect of an abrupt change in the same property. It is possible that whilst gradual changes in stimulus property may have limited overall effect on build-up, the context of a continually varying stimulus may reduce the auditory system's sensitivity to abrupt changes.

In contrast, for Experiment 1, an abrupt change in base frequency produced a substantial resetting effect despite the transition occurring within a gradually varying sequence. Following an abrupt rise or fall of one octave, near-complete resetting occurred and the percept returned to a level similar to the initial extent of segregation at the start of the sequence. The degree of resetting increased with the magnitude of the frequency shift, but was unaffected by the direction of the frequency shift (whether a rise or fall in frequency).

The weaker effect of a single abrupt change for ITD compared with base frequency broadly supports the suggestion that build-up is mediated by frequency-specific neural populations, in accordance with the multi-second neural adaptation model of build-up. The increased tendency for segregation results from habituation of a frequency-specific neural population. Introduction of an abrupt change in frequency would therefore result in stimulation of an alternate (and previously unstimulated) neural population, thereby restarting the process of build-up (Micheyl et al., 2005; Pressnitzer et al., 2008). However, the effect of the single abrupt changes should be considered in view of the gradually varying sequences they were embedded within. Presenting an abrupt change within a continually varying sequence, may render the abrupt change a little less noticeable than the changes occurring within the stimuli used in earlier studies (Rogers and Bregman, 1998; Roberts et al. 2008). This would also account for the suppressive effect of the multiple changes on build-up. It could be argued that the robust effect of abrupt changes on base frequency even when presented in the context of a continually drifting test sequence, is a consequence of the importance of frequency in the formation of auditory objects (Kubovy, 1981; van Valkenburg and Kubovy, 2003).

When considered in this context, the variable effect of single and multiple changes in ITD observed here are consistent with the evidence accumulation account of build-up, as a highly salient abrupt change restarts the process of evidence accumulation (Bregman, 1978) but cannot be explained fully using existing neural accounts (Micheyl et al., 2005; Pressnitzer et al., 2008).

7.2.3 Correlated abrupt changes within static sequences

Chapter 4, focussed solely on the effect of abrupt changes presented within otherwise constant 20-s long sequences. The use of timbral changes in Experiment 3, and level changes in Experiment 4, allowed exploration of whether either a functional account of streaming (Bregman, 1978) and an account based on neural habituation of frequency-specific populations (Micheyl et al., 2005; Pressnitzer et al., 2008) could provide a plausible explanation of effects caused by abrupt changes.

The overall effect of timbre on the dynamics of streaming has rarely been considered in studies of streaming, with a greater focus on the effect of timbral differences between tone subsets. Where sequences of different timbre have been compared, there have been limited differences on the overall level of segregation (Singh and Bregman, 1997; Cusack and Roberts, 2000). Singh and Bregman (1997) adjusted the frequency separation of a sequence (either increasing or decreasing the difference), until the listener recorded that the sequence was now perceived as segregated, providing a measure of the TCB. Using this method, they noted that sequences where both tones had steep rise/slow fall envelopes tended to remain integrated for longer than gradual rise/sharp fall envelopes (only significant for increasing frequency separation cases) . In Experiment 3, however, there was a much more heightened segregated percept for the constant tone-dyad cases in comparison with the pure-tone cases. This difference from earlier findings (Singh and Bregman, 1997; Cusack and Roberts, 2000) could be explained by the alteration in the timing of neural firing for the two stimuli. Whilst the pattern of excitation remained the same for pure tones and their tone-dyad counterparts, the dyads are characterised by a regular 50-Hz modulation envelope. Within the frequency-range of the stimuli used in this experiment (975-1612 Hz) the phase-locking of neurons would provide temporal information about the stimuli, including the modulation envelope of the dyads (cf. Rose et al., 1968). This explanation, whilst speculative, would suggest adaptation by neural populations sensitive to the temporal envelope of the stimulus.

No overall effect of level was visible in Experiment 4, as expected in view of the similar excitation pattern for pure tones within the 12 dB range used here (Rose and Moore, 2000).However, abrupt changes in level were expected to exert an influence on the build-up of segregation. Rogers and Bregman (1998) observed that a 12-dB rise in level at the boundary of an inducer and test sequence, resulted in substantial resetting, whereas a fall of 12 dB had only a limited effect on the test-sequence percept. Using a temporal-discrimination task, Roberts et al. (2008) observed a slightly lesser asymmetry than Rogers and Bregman (1998), but the results were broadly consistent.

Rogers and Bregman (1998) argued that the asymmetry in effects of rises and falls demonstrated the greater importance of abrupt increases in level, because a rise defines the onset of new sound sources. Consistent with these results, an abrupt rise in level of 12 dB resulted in a significant reduction in the extent of segregation (partial resetting) whilst a fall in level produced no significant change. More frequent alternations in level produced suppression similar to that observed in Experiment 2 (alternating lateralisation cued by ITD) suggesting rapid, partial resetting.

An asymmetrical effect of abrupt timbral changes was also found (Experiment 3), but for the first time an overshoot in the extent of segregation was observed on transition from pure tone to tone dyad, whilst resetting was evident following the tone dyad to pure tone transition. More frequent alternations between pure tone and tone dyad sections produced a sawtooth pattern of alternations between high and low segregation levels. In contrast with the overall suppression in response to frequently occurring changes for ITD and level change conditions, the perceptual contrast between pure tone and tone dyad sequences appears to be so strong that rapid resetting and recovery occurs. The strong overshoot and resetting effects may also be due to this strong perceptual contrast between the timbre of pure tones and tone dyads. Alternatively, these effects may be a consequence of adaptation by neural populations sensitive to the temporal regularity of the stimulus.

Considered together, the experiments presented in Chapters 1 and 2 demonstrate that a sudden change in acoustical properties can produce a substantial change in stream segregation, even when the sudden change does not result in any significant change in the pattern of peripheral excitation for a given sequence of sounds. Whilst not precluding some form of neural adaptation account, the variable extent of resetting or overshoot observed in the current experiments does not comfortably fit a model of a habituation response of frequency-specific neural populations (Micheyl et al., 2005; Pressnitzer et al., 2008). Neither can these variable effects (resetting and overshoot) be easily accounted for by a purely functional explanation otherwise, a highly salient property such as source lateralisation cued by ITD would have produced substantial effects. Instead, the novel overshoot effect noted here can be explained to some extent by subtractive adaptation of neurons tuned to the temporal regularity of the stimulus .

A subtractive process could provide an account for the resetting/overshoot asymmetry observed here. Subtractive adaptation acts to reduce the baseline signal in response to a constant stimulus; a proportion of the signal is subtracted from itself so that the amplitude of the response signal falls with time. The contrast of alternations between a highly integrated and highly segregated percept accordingly results in resetting when moving between a portion of the stimulus that tends to be highly segregated to one perceived as integrated, and overshoot in response to a transition in the opposite direction.

These first four thesis experiments exclusively used correlated abrupt changes (i.e., where 'A' and 'B' tone subsets were changed in the same direction and by the same amount. It could be that resetting had a purely functional account, whereby a correlated change is regarded as providing strong evidence of common origin. Whilst failing to adequately explain overshoot, it is worth noting that this rapid rise in segregation could simply reflect the response to the strong perceptual contrast of pure tone and tone dyad sequences.

7.2.4 Anti-correlated abrupt changes

Following on from Experiment 4, the hypothesis that correlated level changes across tone subsets of equal magnitude and in the same direction cue an origin from a single source was examined further. To do so, the effects of correlated and anti-correlated changes were measured. Experiment 5 used 20-s sequences in a 'LHL-' configuration either with correlated transitions of both subsets or synchronous but anti-correlated level transitions.

van Noorden (1975) established that a difference between tone subsets exceeding 3 dB increased the tendency to perceive two streams rather than one. The 6-dB difference used in Experiment 5 also produced more segregation than when 'A' and 'B' subsets had the same level. Consistent with Experiment 4, the correlated alternating cases showed resetting subsequent to rising transitions but falls in level produced little effect.

In the case of the anti-correlated alternating conditions, 'A' and 'B' tones were changed synchronously by 6 dB in opposite directions at the transition points. It was anticipated that if resetting was a consequence of correlated changes in both tone subsets, the anti-correlated transitions would have caused overshoot in response to all transitions.

However, a distinct resetting was observed following the B↑A↓ transitions. If, as for the correlated changes, a rise in level was considered to be the cause of resetting, then this indicates that the 'B'-tone transition had a stronger influence than the 'A'. Additionally, at smaller frequency separations, the opposing A↑B↓ transition resulted in overshoot. This pattern of resetting and overshoot was reduced but still visible for the 6-ST case, but any effect of the anti-correlated changes was essentially absent for the 8-ST case.

To identify which aspects of the two tone subsets (higher vs. lower tone frequency, or higher vs. lower tone density) were responsible for the resetting and overshoot evident in response to anti-correlated changes, Experiment 6 presented the same conditions in both 'LHL-' and 'HLH-' configurations. Sequences with the 'HLH-' structure tended to be perceived as more segregated than those with the 'LHL-' structure, possibly due to the increased density of the high tones, or the higher average frequency of the 'HLH-' triplet in 'HLH-' vs. 'LHL-' sequences. If the rising transitions cause the resetting evident in the correlated alternating cases, as for Experiments 4 and 5, the results from this experiment indicate that the effect is driven largely by 'B'-tone changes, regardless of triplet configuration.

In both experiments, the B↑A↓ transitions caused significant resetting and B↓A↑ transitions caused overshoot. The effect of anti-correlated changes in the context of the two triplet configurations indicate that the directional effects of transitions depend on within-triplet position rather than tone frequency, with B tone transitions mainly responsible for resetting and overshoot. However, the reason for this cannot be clearly identified from these two investigations alone. The ability of anti-correlated changes to cause resetting and overshoot of build-up is more consistent with a neural mechanism based on subtractive adaptation rather than by a functional source grouping argument.

It should be noted that synchronous, anti-correlated changes still indicate a relationship between the two subsets of sounds. Further investigation into the role of factors signalling a relationship between tone subsets, and their perceptual consequences, might perhaps be explored by introducing independent and random changes into the two subsets or changing the properties of one subset but not the other.

7.2.5 Short segregation-promoting inducers

When relatively short induction sequences are used, strong promotion of segregation by a prior stimulus has generally been achieved using constant-frequency inducers (Bregman and Rudnicky, 1975; Beauvois and Meddis, 1997; Rogers and Bregman, 1998; Roberts, Glasberg and Moore, 2008; Haywood and Roberts 2010, 2011, 2013). demonstrated that this segregation level exceeded the level resulting from build-up caused by an otherwise comparable alternating-frequency inducer of the same length. Rogers and Bregman (1993) suggested that this resulted from capture of the tone subset into the pre-existing stream of constant frequency tones, but an alternative theory (Snyder et al. 2008, 2009a, 2009b, 2011; Thompson, Carlyon, and Cusack, 2011) is that segregation promotion may be a result of selective adaptation of frequency-sensitive neurons or frequency-shift detectors.

An alternative method of biasing the percept of a test sequence has been to adjust the frequency separation of a prior sequence. Snyder et al. (2008, 2009a, 2009b, 2011) noted a contrast effect (i.e., a smaller frequency separation in the previous trial consistently led to a more segregated percept of the current trial, whilst a larger separation in the previous trial produced a more integrated percept of the current trial.)

By attenuating a single tone subset in the induction sequence—either 'A' or 'B' tones—Experiment 7 explored whether generating a level difference between tones would facilitate 'stream capture'. Maximal segregation was induced by the infinite attenuation of one tone subset (leaving a single repeating tone), with smaller attenuation cases inducing less segregation in the test sequence. Interestingly, despite preservation of the ABA- triplet rhythm, segregation promotion occurs. This may be due to the increased perceptual distance between tone subsets, permitting capture of the unchanging subset.

To follow on from Experiment 7 and examine whether the direction of a perceptual change would affect promotion of segregation by an inducer, Experiment 8 explored the influence of varying the frequency separation of an inducer using 'HLH-' sequences. Regardless of whether the frequency separation between subsets where increased or decreased at the inducer-test boundary, increased segregation of the test sequence was observed . The contrasting results of this study compared with those of Snyder at al. (2008, 2009) is likely to be a consequence of the elimination of any silent intervals in Experiment 8. Preserving the inter-stimulus intervals between the inducer and test sequences may have allowed capture of the H tones out of the test sequence. Another interesting feature of Experiment 7 was that the greatest extent of segregation was induced by the case where the L tone was shifted up to the H tone frequency, producing a rapidly repeating high tone with the same rhythm as the test sequence consistent with the assertion than rhythmic similarity is required for effective stream biasing (Snyder and Weintraub, 2011).

Rather than changing the level or frequency of one subset of tones, Experiment 9 instead attempted to capture out one subset using an alternative method. A tone complex, harmonically related to the L tone in a 'HLH-' sequence was presented synchronously with the L tone, intended to fuse with the tone (simultaneous capture). Successful fusion was anticipated to separate perceptually the H and L tones due to the distinct timbral difference between pure and complex tones. However, it appeared that by maintaining the frequency separation of H and L tones (upper edge of the fused complex) across the inducer-test boundary, perceptual capture may have occurred but did not disrupt the rhythm of the sequence.

The same harmonic complex presented asynchronously (i.e., during the silent intervals between triplets) suppressed build-up during the induction sequence, leading to a segregation level comparable to that of the silent (no inducer) case. This outcome provided additional evidence to that from Experiment 7, demonstrating the importance of rhythm on stream biasing.

In summary, the experiments presented in Chapter 6 demonstrated that segregation promotion or capture of either tone subset can be achieved by adjusting the perceptual distance (in frequency or level) between the inducer tone subsets, and that stream biasing depends upon maintaining the rhythm across the inducer-test boundary. As pointed out by Haywood and Roberts (2013), these near-instantaneous effects are unlikely to result from slower adaptation of frequency-specific neurons, as has been suggested for the multi-second build-up produced by on-going alternating-frequency sequences.

7.3 Concluding remarks

In conclusion, the experiments presented within this thesis demonstrated three main findings. First, that the introduction of gradual changes within a sequence does not exert a significant influence on the build-up of stream segregation although they may reduce the sensitivity to single abrupt changes, such that transitions need to be larger to produce a comparable effect to those occurring within otherwise constant sequences.

Second, that the effect of an abrupt change depends on the property being altered, in some cases causing substantial resetting or overshoot regardless of whether these shifts are correlated or anti-correlated. Third, effective capture of a single sub-stream is not limited only to constant frequency inducers whose frequency matches that of one of the tone subsets in the test sequence. By moving one tone subset either closer to or further from the other at the inducer-test boundary, whilst the other is kept fixed, a highly segregated inducer can also be produced. The stream biasing effect of an inducer is dependent on maintaining rhythmic regularity across the inducer-test boundary.

Taken together, these findings indicate that the dynamics of stream segregation are considerably more complicated than has previously been realised (see table 7.1 for a summary list of which results were consistent with current models of stream segregation). Although further research would be required to clarify the mechanisms underlying these outcomes, and their functional significance, the finding of directional effects such that abrupt changes in sequence properties lead to resetting of stream segregation in some cases but to overshoot in others – suggest the involvement of a neural mechanism based on subtractive adaptation.

Table 7.1: List of all experiments presented within this thesis, showing whether the results of each were broadly consistent with either the multi-second neural adaptation model (Micheyl et al., 2005; Pressnitzer et al., 2008), or the evidence accumulation model (Bregman, 1978) of stream segregation. In the cases of Experiments 5 & 6, neither of these current models of stream segregation adequately account for the observed effects.

Chapter	Experiment	Stimulus properties manipulated	Multi-second Neural Adaptation Model	Evidence Accumulation Model	Comments
3	1	Gradual and abrupt changes in frequency	Yes	Yes	*Without modification, neither model explains the partial resetting observed with smaller changes.*
	2	Gradual and abrupt changes in ITD	Yes	Yes	
4	3	Abrupt changes in timbre (with minimal changes in excitation pattern)	No	Yes	*Current neural adaptation models do not explain 'overshoot' effects but a subtractive adaptation mechanism could underlie these effects.*
	4	Abrupt changes in level	No	Yes	*Resetting effect of level changes were smaller than expected from the evidence accumulation account.*
5	5	Correlated and anti-correlated level changes	No	No	*Overshoot/ resetting was consistent with a subtractive adaptation mechanism.*
	6	The effect of triplet structure on anti-correlated level change	No	No	
6	7	Level differences between tone subsets in an inducer sequence	No*	Yes	*Effects consistent with 'perceptual capture' (Bregman & Rudnicky, 1975; Rogers & Bregman, 1993; Haywood & Roberts, 2013).*
	8	Varying Δf_{AB} of an inducer sequence relative Δf_{AB} of the test sequence	No*	Yes	*(*)Note that the almost immediate effect of stimulus change at the inducer-test boundary is also inconsistent with the slow adaptation mechanism proposed by Snyder et al. (2009).*
	9	Accompanying the induction sequence with a harmonic captor complex	No*	Yes	

Appendix A

Appendix A

A.1 Chapter 4 Tables

A.1.1 Experiment 3

TABLE A.1: Pairwise Comparison of A-B frequency separations for Constant Cases Only.

Δf_{AB} (ST)		Mean Difference (%)	p	η_p^2
4	**6**	**-13.4**	**0.028**	**0.001**
	8	**-16.2**	**0.045**	**0.004**
6	**4**	**13.4**	**0.028**	**0.001**
	8	-2.8	0.028	0.342
8	**4**	**16.2**	**0.045**	**0.004**
	6	2.8	0.028	0.342

TABLE A.2: Pairwise Comparison of Time Interval for Constant Cases Only.

(I) TimeInterval	(J) TimeInterval	Mean Difference [I-J](%)	Std. Error(%)	p
1	2	**-7.13**	**1.46**	**<0.001**
	3	**-12.13**	2.42	**<0.001**
	4	**-16.17**	**3.41**	**0.001**
	5	**-20.18**	**3.67**	**<0.001**
	6	**-23.86**	**4.12**	**<0.001**
	7	**-28.60**	**4.90**	**<0.001**
	8	**-30.65**	**5.17**	**<0.001**
	9	**-33.12**	**5.69**	**<0.001**
	10	**-36.75**	**6.13**	**<0.001**
	11	**-36.96**	**6.27**	**<0.001**
	12	**-36.81**	**6.21**	**<0.001**
	13	**-37.17**	**6.19**	**<0.001**
	14	**-36.05**	**5.98**	**<0.001**
	15	**-36.18**	**5.88**	**<0.001**
	16	**-36.00**	**5.78**	**<0.001**
	17	**-36.50**	**5.73**	**<0.001**
	18	**-36.25**	**5.59**	**<0.001**
	19	**-36.84**	**5.61**	**<0.001**
19	**1**	**36.84**	**5.61**	**<0.001**
	2	**29.70**	**5.08**	**<0.001**
	3	**24.71**	**4.33**	**<0.001**
	4	**20.67**	**4.29**	**0.001**
	5	**16.66**	**3.85**	**0.001**
	6	**12.98**	**3.20**	**0.002**
	7	**8.24**	**2.78**	**0.013**
	8	**6.19**	**2.45**	**0.028**
	9	3.71	2.25	0.126
	10	0.09	2.53	0.973
	11	-0.12	2.43	0.960
	12	0.02	2.18	0.991
	13	-0.33	1.94	0.868
	14	0.79	1.75	0.661
	15	0.65	1.24	0.609
	16	0.84	0.94	0.394
	17	0.34	0.68	0.629
	18	0.59	0.35	0.118

TABLE A.3: Pairwise Comparison of A-B frequency separations for Constant vs Rapidly Alternating Cases Only.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J](%)	Std. Error(%)	p
4	**6**	**-9.6**	**21.2**	**0.001**
	8	**-12.6**	**35.4**	**0.004**
6	4	**9.6**	**21.2**	**0.001**
	8	-3.0	24.0	0.235
8	4	**12.6**	**35.4**	**0.005**
	6	3.0	24.0	0.235

Table A.4: Pairwise Comparison of A-B frequency separations for Constant Cases vs Alternating (13 triplet).

(I) Δf_{AB}	(J) Δf_{AB}	Mean Difference (I-J)	Std. Error	Sig.
4	**6**	**-9.97**	**1.95**	**<0.001**
	8	**-14.80**	**3.87**	**0.003**
6	**4**	**9.97**	**1.95**	**<0.001**
	8	-4.83	2.67	0.097
8	**4**	**14.80**	**3.87**	**0.003**
	6	4.83	2.67	0.097

A.2 Chapter 5 Tables

A.2.1 Experiment 5

TABLE A.5: Pairwise Comparison of Time Interval for fixed A&B difference and anti-correlated change conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	2	**-9.8**	**3.0**	**0.007**
	3	-23.7	**5.1**	**0.001**
	4	**-34.3**	**6.2**	**<0.001**
	5	**-41.3**	**6.2**	**<0.001**
	6	**-49.0**	**6.4**	**<0.001**
	7	**-55.0**	**6.2**	**<0.001**
	8	**-57.8**	**5.4**	**<0.001**
	9	**-56.5**	**4.2**	**<0.001**
	10	**-59.3**	**3.9**	**<0.001**
	11	**-62.4**	**3.4**	**<0.001**
	12	**-65.0**	**3.2**	**<0.001**
	13	-65.5	2.6	<0.001
	14	**-67.6**	**2.3**	**<0.001**
	15	**-69.5**	**2.0**	**<0.001**
	16	**-70.0**	**2.1**	**<0.001**
	17	**-67.3**	**2.0**	**<0.001**
	18	**-68.9**	**2.1**	**<0.001**
	19	**-70.9**	**2.0**	**<0.001**
19	**1**	**70.9**	**2.0**	**<0.001**
	2	**61.1**	**3.5**	**<0.001**
	3	**47.1**	**5.2**	**<0.001**
	4	**36.6**	**6.1**	**<0.001**
	5	**29.6**	**5.9**	**<0.001**
	6	**21.9**	**6.2**	**0.005**
	7	**15.9**	**6.0**	**0.024**
	8	**13.1**	**5.2**	**0.030**
	9	**14.3**	**4.0**	**0.004**
	10	**11.6**	**3.8**	**0.011**
	11	**8.5**	**3.2**	**0.022**
	12	5.9	2.9	0.067
	13	**5.4**	**2.3**	**0.037**
	14	3.3	2.1	0.145
	15	1.4	1.8	0.464
	16	0.9	1.4	0.546
	17	**3.6**	**1.1**	**0.009**
	18	**2.0**	**0.7**	**0.013**

TABLE A.6: Pairwise Comparison of A-B frequency separations for fixed all high and all low level conditions (A & B tones at the same level).

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	*p*
4	6	-20.7	2.44	<0.001
	8	-31.3	4.26	<0.001
6	4	20.7	2.44	<0.001
	8	-10.7	2.79	0.003
8	4	31.3	4.26	<0.001
	6	10.7	2.79	0.003

TABLE A.7: Pairwise Comparison of A-B frequency separations for average of fixed all-same and fixed all-different conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	*p*
4	6	-16.6	27.2	<0.001
	8	-26.2	43.2	<0.001
6	4	16.6	27.2	<0.001
	8	-9.6	20.5	0.001
8	4	26.2	43.2	<0.001
	6	9.6	20.5	0.001

TABLE A.8: Pairwise Comparison of A-B frequency separations for fixed A&B difference and anti-correlated change conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	*p*
4	6	-17.2	2.5	<0.001
	8	-29.4	4.0	<0.001
6	4	17.2	2.5	<0.001
	8	12.2	2.7	0.001
8	4	29.4	4.0	<0.001
	6	12.2	2.7	0.001

TABLE A.9: Pairwise Comparison of A-B frequency separations for fixed A&B difference and anti-correlated change conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-11.8**	**3.0**	**0.002**
	8	**-21.6**	**4.8**	**0.001**
6	**4**	**11.8**	**3.0**	**0.002**
	8	**9.8**	**2.2**	**0.001**
8	**4**	**21.6**	**4.8**	**0.001**
	6	**9.8**	**2.2**	**0.001**

Table A.10: Pairwise Comparison of Time Interval for fixed high and low level conditions (A & B tones at the same level).

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-7.2**	**1.4**	**<0.001**
	3	**-17.8**	**3.5**	**<0.001**
	4	**-27.8**	**4.6**	**0.001**
	5	**-36.1**	**5.0**	**<0.001**
	6	**-41.7**	**5.1**	**<0.001**
	7	**-45.7**	**5.1**	**<0.001**
	8	**-50.0**	**4.9**	**<0.001**
	9	**-54.0**	**4.8**	**<0.001**
	10	**-57.1**	**4.8**	**<0.001**
	11	**-58.7**	**4.2**	**<0.001**
	12	**-61.2**	**3.8**	**<0.001**
	13	**-62.4**	**4.0**	**<0.001**
	14	**-64.0**	**4.0**	**<0.001**
	15	**-64.2**	**3.8**	**<0.001**
	16	**-64.3**	**3.0**	**<0.001**
	17	**-66.2**	**2.3**	**<0.001**
	18	**-67.5**	**2.2**	**<0.001**
	19	**-69.2**	**2.4**	**<0.001**
19	**1**	**69.2**	**2.4**	**<0.001**
	2	**62.0**	**2.8**	**<0.001**
	3	**51.5**	**3.6**	**<0.001**
	4	**41.4**	**4.4**	**<0.001**
	5	**33.2**	**4.5**	**<0.001**
	6	**27.5**	**4.2**	**<0.001**
	7	**23.5**	**4.2**	**<0.001**
	8	**19.3**	**4.2**	**0.001**
	9	**15.2**	**3.9**	**0.002**
	10	**12.2**	**3.9**	**0.009**
	11	**10.6**	**3.3**	**0.008**
	12	**8.1**	**2.7**	**0.011**
	13	**6.8**	**2.5**	**0.010**
	14	5.2	2.6	0.073
	15	5.1	2.3	0.053
	16	**4.9**	**1.7**	**0.015**
	17	**3.0**	**1.0**	**0.010**
	18	1.7	0.8	0.060

TABLE A.11: Pairwise Comparison of Time Interval means of fixed A&B same and fixed A&B different conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-8.8**	**1.4**	**0.002**
	3	**-21.1**	**3.5**	**<0.001**
	4	**-31.7**	**4.6**	**<0.001**
	5	**-39.4**	**5.0**	**<0.001**
	6	**-45.1**	**5.1**	**<0.001**
	7	**-49.3**	**5.1**	**<0.001**
	8	**-53.4**	**4.9**	**<0.001**
	9	**-57.7**	**4.8**	**<0.001**
	10	**-60.4**	**4.8**	**<0.001**
	11	**-62.0**	**4.2**	**<0.001**
	12	**-65.1**	**3.8**	**<0.001**
	13	**-67.0**	**4.0**	**<0.001**
	14	**-67.7**	**4.0**	**<0.001**
	15	**-68.4**	**3.8**	**<0.001**
	16	**-69.1**	**3.0**	**<0.001**
	17	**-70.3**	**2.3**	**<0.001**
	18	**-72.1**	**2.2**	**<0.001**
	19	**-73.3**	**2.4**	**<0.001**
19	**1**	**73.3**	**2.0**	**<0.001**
	2	**64.5**	**2.7**	**<0.001**
	3	**52.2**	**4.0**	**<0.001**
	4	**41.6**	**4.9**	**<0.001**
	5	**33.9**	**5.2**	**<0.001**
	6	**28.2**	**5.3**	**<0.001**
	7	**24.0**	**5.0**	**0.001**
	8	**19.9**	**4.8**	**0.002**
	9	**15.6**	**4.5**	**0.005**
	10	**12.9**	**4.2**	**0.010**
	11	**11.3**	**3.6**	**0.010**
	12	**8.2**	**3.2**	**0.027**
	13	**6.3**	**2.9**	**0.052**
	14	5.6	2.7	0.065
	15	4.9	2.3	0.055
	16	**4.2**	**1.7**	**0.027**
	17	**3.0**	**0.9**	**0.005**
	18	1.2	0.6	0.069

Table A.12: Pairwise Comparison of Time Interval for fixed A&B difference and anti-correlated change conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	2	**-9.8**	**3.0**	**0.007**
	3	**-23.7**	**5.1**	**0.001**
	4	**-34.3**	**6.2**	**<0.001**
	5	**-41.3**	**6.2**	**<0.001**
	6	**-49.0**	**6.4**	**<0.001**
	7	**-55.0**	**6.2**	**<0.001**
	8	**-57.8**	**5.4**	**<0.001**
	9	**-56.5**	**4.2**	**<0.001**
	10	**-59.3**	**3.9**	**<0.001**
	11	**-62.4**	**3.4**	**<0.001**
	12	**-65.0**	**3.2**	**<0.001**
	13	**-65.5**	**2.6**	**<0.001**
	14	**-67.6**	**2.3**	**<0.001**
	15	**-69.5**	**2.0**	**<0.001**
	16	**-70.0**	**2.1**	**<0.001**
	17	**-67.3**	**2.0**	**<0.001**
	18	**-68.9**	**2.1**	**<0.001**
	19	**-70.9**	**2.0**	**<0.001**
19	**1**	**70.9**	**2.0**	**<0.001**
	2	**61.1**	**3.5**	**<0.001**
	3	**47.1**	**5.2**	**<0.001**
	4	**36.6**	**6.1**	**<0.001**
	5	**29.6**	**5.9**	**<0.001**
	6	**21.9**	**6.2**	**0.005**
	7	**15.9**	**6.0**	**0.024**
	8	**13.1**	**5.2**	**0.030**
	9	**14.3**	**4.0**	**0.004**
	10	**11.6**	**3.8**	**0.011**
	11	**8.5**	**3.2**	**0.022**
	12	**5.9**	**2.9**	**0.067**
	13	**5.4**	**2.3**	**0.037**
	14	3.3	2.1	0.145
	15	1.4	1.8	0.464
	16	**0.9**	**1.4**	**0.546**
	17	**3.6**	**1.1**	**0.009**
	18	2.0	0.7	0.013

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Table A.13: Pairwise Comparison of A-B frequency separations for LHL- and HLH-fixed conditions (A & B = same level.)

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-13.8**	**5.4**	**0.028**
	8	**-3.01**	**7.1**	**0.001**
6	**4**	**13.8**	**5.4**	**0.028**
	8	**-16.4**	**4.9**	**0.007**
8	**4**	**30.1**	**7.1**	**0.001**
	6	**16.4**	**4.9**	**0.007**

Table A.14: Pairwise Comparison of A-B frequency separations for LHL- fixed conditions (A & B same, and both A & B constant difference conditions.)

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-10.6**	**4.4**	**<0.001**
	8	**-23.1**	**7.6**	**<0.001**
6	**4**	**10.6**	**4.4**	**<0.001**
	8	**-12.5**	**3.9**	**0.001**
8	**4**	**23.1**	**7.6**	**<0.001**
	6	**12.5**	**3.9**	**0.001**

Table A.15: Pairwise Comparison of A-B frequency separations for HLH- fixed conditions (A&B same, and both A&B constant difference conditions.)

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-17.0**	**5.3**	**0.008**
	8	**-27.1**	**6.4**	**0.002**
6	**4**	**17.0**	**5.3**	**0.008**
	8	**-10.1**	**2.9**	**0.005**
8	**4**	**27.1**	**6.6**	**0.002**
	6	**10.1**	**2.9**	**0.005**

Table A.16: Pairwise Comparison of A-B frequency separations for LHL- fixed A & B different and alternating conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-11.4**	**4.3**	**0.022**
	8	**-19**	**6.2**	**0.001**
6	**4**	**11.4**	**4.3**	**0.022**
	8	**7.6**	**2.4**	**0.009**
8	**4**	**19**	**6.2**	**0.010**
	6	**7.6**	**2.4**	**0.009**

Table A.17: Pairwise Comparison of A-B frequency separations for HLH- fixed A & B different and alternating conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-12.0**	**4.1**	**0.015**
	8	**-20.0**	**6.5**	**0.010**
6	**4**	**12.0**	**4.1**	**0.015**
	8	**8.1**	**2.5**	**0.007**
8	**4**	**20.0**	**6.5**	**0.010**
	6	**8.1**	**2.5**	**0.007**

Table A.18: Pairwise Comparison of Time Interval for LHL- and HLH- fixed conditions (A & B same.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-2.9**	**0.7**	**0.003**
	3	**-6.5**	**1.8**	**0.004**
	4	**-12.9**	**3.2**	**0.002**
	5	**-18.7**	**3.6**	**<0.001**
	6	**-21.6**	**4.2**	**<0.001**
	7	**-24.7**	**4.8**	**<0.001**
	8	**-27.2**	**5.1**	**<0.001**
	9	**-29.4**	**5.6**	**<0.001**
	10	**-31.6**	**6.4**	**<0.001**
	11	**-33.5**	**6.4**	**<0.001**
	12	**-36.0**	**6.6**	**<0.001**
	13	**-37.7**	**7.4**	**<0.001**
	14	**-38.9**	**7.5**	**<0.001**
	15	**-40.4**	**7.9**	**<0.001**
	16	**-41.2**	**8.0**	**<0.001**
	17	**-39.2**	**7.9**	**<0.001**
	18	**-37.8**	**7.5**	**<0.001**
	19	**-39.0**	**7.9**	**<0.001**
19	**1**	**39.0**	**7.9**	**<0.001**
	2	**36.1**	**8.1**	**0.001**
	3	**32.5**	**7.5**	**0.001**
	4	**26.1**	**6.5**	**0.002**
	5	**20.3**	**6.5**	**0.010**
	6	**17.4**	**5.9**	**0.013**
	7	**14.3**	**5.4**	**0.022**
	8	**11.8**	**4.7**	**0.029**
	9	**9.6**	**3.9**	**0.031**
	10	7.4	3.4	0.051
	11	5.5	3.0	0.100
	12	3.0	2.7	0.296
	13	1.3	2.4	0.597
	14	0.1	2.3	0.980
	15	-1.4	2.2	0.530
	16	-2.2	1.8	0.249
	17	-0.2	1.6	0.904
	18	1.2	1.1	0.284

Table A.19: Pairwise Comparison of Time Interval for LHL- fixed conditions (A & B same, and both A & B constant difference conditions.)

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	**-3.1**	**1.0**	**0.009**
	3	**-8.2**	2.4	**0.005**
	4	**-14.7**	4.3	**0.006**
	5	**-20.4**	**5.5**	**0.003**
	6	**-24.5**	**6.1**	**0.002**
	7	**-27.6**	**6.3**	**0.001**
	8	**-29.9**	**6.5**	**0.001**
	9	**-33.2**	**6.9**	**0.001**
	10	**-35.2**	**7.6**	**0.001**
	11	**-36.7**	**8.1**	**0.001**
	12	**-39.4**	**8.7**	**0.001**
	13	**-41.0**	**9.0**	**0.001**
	14	**-41.8**	**8.9**	**0.001**
	15	**-41.8**	**8.8**	**0.001**
	16	**-42.6**	**8.8**	**0.001**
	17	**-42.7**	**8.6**	**0.000**
	18	**-43.0**	**8.9**	**0.001**
	19	**-43.3**	**9.2**	**0.001**
19	**1**	**43.3**	**9.2**	**0.001**
	2	**40.2**	**9.3**	**0.001**
	3	**35.1**	**8.7**	**0.002**
	4	**28.6**	**7.5**	**0.003**
	5	**22.8**	**6.8**	**0.006**
	6	**18.7**	**6.0**	**0.010**
	7	**15.7**	**5.3**	**0.013**
	8	**13.3**	**4.8**	**0.017**
	9	**10.1**	**4.3**	**0.038**
	10	8.0	3.8	0.057
	11	6.6	3.5	0.089
	12	3.9	3.6	0.302
	13	2.3	3.3	0.494
	14	1.4	2.9	0.638
	15	1.4	2.6	0.586
	16	0.6	1.8	0.724
	17	0.5	1.4	0.709
	18	0.2	1.0	0.825

Table A.20: Pairwise Comparison of Time Interval for HLH- fixed conditions (A & B same, and both A & B constant difference conditions

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	**2**	**-4.0**	**1.3**	**0.013**
	3	**-8.8**	**2.7**	**0.007**
	4	**-16.7**	**4.1**	**0.002**
	5	**-24.5**	**4.9**	**<0.001**
	6	**-29.0**	**5.6**	**<0.001**
	7	**-32.1**	**5.9**	**<0.001**
	8	**-35.3**	**6.7**	**<0.001**
	9	**-37.2**	**7.0**	**<0.001**
	10	**-37.4**	**7.3**	**<0.001**
	11	**-39.5**	**7.3**	**<0.001**
	12	**-41.2**	**7.4**	**<0.001**
	13	**-41.6**	**7.6**	**<0.001**
	14	**-43.1**	**7.7**	**<0.001**
	15	**-44.4**	**8.2**	**<0.001**
	16	**-43.9**	**8.5**	**<0.001**
	17	**-43.3**	**8.8**	**<0.001**
	18	**-44.0**	**8.9**	**<0.001**
	19	**-45.5**	**9.0**	**<0.001**
19	**1**	**45.5**	**9.0**	**<0.001**
	2	**41.5**	**9.4**	**0.001**
	3	**36.6**	**9.2**	**0.002**
	4	**28.7**	**8.8**	**0.007**
	5	**20.9**	**8.1**	**0.026**
	6	**16.5**	**7.1**	**0.040**
	7	13.3	6.1	0.051
	8	10.1	4.9	0.065
	9	8.2	4.1	0.068
	10	**8.1**	**3.3**	**0.030**
	11	6.0	2.8	0.054
	12	4.2	2.6	0.128
	13	3.9	2.3	0.119
	14	2.4	1.7	0.187
	15	1.0	1.1	0.377
	16	1.6	0.9	0.110
	17	2.1	1.0	0.058
	18	**1.5**	**0.5**	**0.016**

Table A.21: Pairwise Comparison of Time Interval for LHL- fixed A & B different and alternating conditions

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	**2**	**-3.4**	**1.0**	**0.007**
	3	**-8.8**	**2.3**	**0.002**
	4	**-15.3**	**4.0**	**0.003**
	5	**-25.2**	**5.2**	**0.001**
	6	**-32.3**	**6.1**	**<0.001**
	7	**-36.2**	**6.7**	**<0.001**
	8	**-39.1**	**6.9**	**<0.001**
	9	**-39.9**	**6.6**	**<0.001**
	10	**-40.9**	**6.9**	**<0.001**
	11	**-42.9**	**7.2**	**<0.001**
	12	**-44.4**	**7.9**	**<0.001**
	13	**-46.6**	**7.8**	**<0.001**
	14	**-47.7**	**8.0**	**<0.001**
	15	**-48.0**	**8.1**	**<0.001**
	16	**-48.7**	**8.0**	**<0.001**
	17	**-47.0**	**7.7**	**<0.001**
	18	**-47.4**	**7.7**	**<0.001**
	19	**-47.2**	**7.7**	**<0.001**
19	**1**	**47.2**	**7.7**	**<0.001**
	2	**43.9**	**7.9**	**<0.001**
	3	**38.4**	**7.6**	**<0.001**
	4	**32.0**	**6.4**	**<0.001**
	5	**22.0**	**5.5**	**0.002**
	6	**15.0**	**4.7**	**0.008**
	7	**11.0**	**4.0**	**0.018**
	8	**8.1**	**3.3**	**0.032**
	9	**7.3**	**3.1**	**0.038**
	10	**6.3**	**2.7**	**0.037**
	11	4.3	2.5	0.118
	12	2.8	2.5	0.279
	13	0.6	1.7	0.714
	14	-0.5	1.7	0.777
	15	-0.8	1.7	0.647
	16	-1.5	1.3	0.283
	17	0.3	1.1	0.802
	18	-0.2	0.7	0.797

Table A.22: Pairwise Comparison of Time Interval for HLH- fixed A & B different and alternating conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	*p*
1	2	**-4.6**	**1.4**	**0.006**
	3	**-9.9**	**2.5**	**0.002**
	4	**-17.5**	**3.6**	**0.001**
	5	**-30.2**	**4.7**	**<0.001**
	6	**-37.1**	**5.6**	**<0.001**
	7	**-39.7**	**5.9**	**<0.001**
	8	**-40.9**	**6.2**	**<0.001**
	9	**-41.2**	**6.2**	**<0.001**
	10	**-42.1**	**6.4**	**<0.001**
	11	**-44.2**	**6.6**	**<0.001**
	12	**-46.3**	**6.7**	**<0.001**
	13	**-48.5**	**6.5**	**<0.001**
	14	**-48.8**	**6.6**	**<0.001**
	15	**-48.6**	**6.8**	**<0.001**
	16	**-48.0**	**7.1**	**<0.001**
	17	**-47.6**	**7.5**	**<0.001**
	18	**-48.4**	**7.3**	**<0.001**
	19	**-49.4**	**7.2**	**<0.001**
19	**1**	**49.4**	**7.2**	**<0.001**
	2	**44.8**	**7.7**	**<0.001**
	3	**39.5**	**7.6**	**<0.001**
	4	**31.9**	**7.4**	**0.001**
	5	**19.2**	**6.6**	**0.014**
	6	**12.3**	**5.5**	**0.049**
	7	9.7	4.6	0.060
	8	**8.5**	**3.6**	**0.036**
	9	**8.2**	**3.1**	**0.023**
	10	**7.3**	**2.5**	**0.015**
	11	**5.2**	2.2	**0.041**
	12	3.1	2.2	0.186
	13	0.9	1.8	0.607
	14	0.6	1.4	0.666
	15	0.8	1.2	0.522
	16	1.4	0.9	0.152
	17	**1.8**	**0.7**	**0.018**
	18	1.0	0.5	0.074

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TABLE A.23: Pairwise Comparison of A-B frequency separations across all conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-17.0**	2.29	**<0.001**
	8	-27.7	3.79	**<0.001**
6	4	**17.0**	2.29	**<0.001**
	8	**-10.7**	2.22	**0.001**
8	4	27.7	3.79	**<0.001**
	6	**10.7**	2.22	**0.001**

TABLE A.24: Pairwise Comparison of time interval across all conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	-1.68	0.84	0.071
	3	**-14.4**	**2.85**	**<0.001**
	4	**-25.0**	**3.71**	**<0.001**
	5	**-29.8**	**3.61**	**<0.001**
	6	**-31.6**	**3.54**	**<0.001**
	7	**-32.6**	**3.67**	**<0.001**
	8	**-33.9**	**3.72**	**<0.001**
	9	**-34.9**	**3.71**	**<0.001**
	10	**-36.2**	**3.67**	**<0.001**
	11	**-37.3**	**3.69**	**<0.001**
11	1	37.3	3.7	0.454
	2	35.6	3.4	0.430
	3	22.8	4.0	0.316
	4	12.2	4.1	0.212
	5	7.5	3.6	0.154
	6	5.6	3.0	0.122
	7	4.6	2.5	0.102
	8	3.4	1.8	0.073
	9	2.1	1.2	0.051
	10	**1.0**	**0.5**	**0.022**

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TABLE A.25: Pairwise Comparison of A-B frequency separations across all conditions.

[I] Δf_{AB} (ST)	[J] Δf_{AB} (ST)	Mean Difference [I-J] (%)	Std. Error (%)	p
4	**6**	**-17.0**	2.29	**<0.001**
	8	-27.7	3.79	**<0.001**
6	4	**17.0**	2.29	**<0.001**
	8	-10.7	2.22	**0.001**
8	4	27.7	3.79	**<0.001**
	6	**10.7**	2.22	**0.001**

TABLE A.26: Pairwise Comparison of time interval across all conditions.

(I) Time Interval	(J) Time Interval	Mean Difference [I-J] (%)	Std. Error (%)	p
1	2	-1.68	0.84	0.071
	3	**-14.40**	**2.85**	**<0.001**
	4	**-25.00**	**3.71**	**<0.001**
	5	**-29.80**	**3.61**	**<0.001**
	6	**-31.60**	**3.54**	**<0.001**
	7	**-32.60**	**3.67**	**<0.001**
	8	**-33.90**	**3.72**	**<0.001**
	9	**-34.90**	**3.71**	**<0.001**
	10	**-36.20**	**3.67**	**<0.001**
	11	**-37.30**	**3.69**	**<0.001**
11	1	37.30	3.69	0.454
	2	35.60	3.36	0.430
	3	22.80	3.98	0.316
	4	12.20	4.07	0.212
	5	7.48	3.58	0.154
	6	5.62	2.97	0.122
	7	4.63	2.54	0.102
	8	3.39	1.79	0.073
	9	2.41	1.21	0.051
	10	**1.03**	**0.52**	**0.022**

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