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# Binaural beat salience

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ABSTRACT

Previous studies of binaural beats have noted individual variability and response lability, but little attention has been paid to the salience of the binaural beat percept. The purpose of this study was to gauge the strength of the binaural beat percept by matching its salience to that of sinusoidal amplitude modulation (SAM), and to then compare rate discrimination for the two types of fluctuation. Rate discrimination was measured for standard rates of 4, 8, 16, and 32 Hz – all in the 500-Hz carrier region. Twelve normal-hearing adults participated in this study. The results indicated that discrimination acuity for binaural beats is similar to that for SAM tones whose depths of modulation have been adjusted to provide equivalent modulation salience. The matched-salience SAM tones had relatively shallow depths of modulation, suggesting that the perceptual strength of binaural beats is relatively weak, although all listeners perceived them. The Weber fraction for detection of an increase in binaural beat rate is roughly constant across beat rates, at least for rates above 4 Hz, as is rate discrimination for SAM tones.



## 1. Introduction

In his compendium of *Curious Binaural Phenomena*, Tobias (1972) includes the phenomenon of binaural beats. These beats refer to a fluctuation that is perceived when two relatively low frequency tones differing slightly in frequency are presented independently to the two ears. The rate of fluctuation depends on the frequency separation of the two tones ($\Delta f$), as does the nature of the percept itself: As $\Delta f$ increases – and, concomitantly, the beat rate increases – the percept transitions from a sense of intracranial motion, to loudness fluctuation, to roughness, until in the limit the tones are perceived discretely at the two ears in the absence of a beat percept (Rutschmann and Rubinstein, 1965). These perceptual transitions represent a continuum, in that rate-defined boundaries are indistinct. Presumably, Tobias considered binaural beats to be ‘curious’ because the findings at that time were sparse and oddly disjointed, in that some did not conform easily to accepted frameworks of binaural processing. Indeed, Wever (1949) referred to the study of binaural beats as a “rather confused area.” For example, one study reported that binaural beats could be perceived even if the tone to one ear was 20 dB below audibility threshold (Groen, 1964) [more recent work has not supported this (Gu et al., 1995)], while another study indicated that there was marginal overlap in the frequency regions giving rise to binaural beats in males and females, although this frequency region varied in females in conjunction with the menstrual cycle (Tobias, 1965).

Despite these somewhat scattered observations, a general consensus did emerge from the early studies on core stimulus attributes optimal for binaural beat generation. Specifically, the likelihood of perceiving a beat depended strongly on the frequency region and $\Delta f$ of the tone pair, such that beats were most prevalent for lower frequency tones with relatively small spectral separations (Licklider et al., 1950; Perrott and Musicant, 1977). More recent studies have demonstrated that the binaural beat is robust for wide-band stimuli such as ‘phase-warped’ (Siveke et al., 2008), or ‘phase-and-amplitude-warped’ (Akeroyd, 2010) bands of noise, where spectral components to one ear are transposed relative to the other ear (Dietz et al., 2008). In these stimuli, either the phase components alone or the phase and amplitude components of a wide-band noise are shifted in one ear relative to the other ear by a fixed frequency step (i.e., $\Delta f$), corresponding to the binaural beat rate. Such wide-band stimuli can generate more pronounced sensations of intracranial motion than can tone pairs. For example, Akeroyd (2010) demonstrated that, for beat rates less than about 5 Hz, a relatively-wide binaural beat noise consistently resulted in

*Abbreviations:* SAM, sinusoidal amplitude modulation; dB, decibel; Hz, Hertz; IPD, interaural phase difference; ILD, interaural level difference; JND, just noticeable difference; ms, millisecond; 2AFC, 2-alternative, forced-choice; HL, hearing level; yrs, years; DC, direct current; ANOVA, analysis of variance; SPL, sound pressure level; SL, sensation level.

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a reliable sense of intracranial motion whereas a tonal binaural beat was much less likely to do so.

Although there is general consensus on core stimulus attributes for binaural beat generation, the focus of this study is on the question of the strength of the binaural beat percept for tone pairs. This question arises because the literature on binaural beats reveals disparate views on individual variability. Békésy (reported in Tobias (1972)) estimated that only about 50% of listeners are able to perceive binaural beats, whereas it is implicit in other studies that the percept is available to all listeners (e.g., Tobias, 1965). This disparity reflects, in part, methodological differences. Tobias (1963) demonstrated that a listener was far more likely to perceive a binaural beat if the tone pair alternated with a non-beating steady tone, as a reference, than if the beating tone pair was presented alone. Nevertheless, there remain indications that the perception of binaural beats is not obligatory. For example, Licklider et al. (1950) noted that for higher-frequency tones ($\geq$1000 Hz) the perception of binaural beats required the listener to be “properly set” and not fatigued. The somewhat tenuous nature of the binaural beat percept appears to be particularly pronounced for non-optimal stimulus configurations where the percept is faint at best. For example, McFadden and Pasanen (1975) studied the weak binaural beats generated by interaural envelope disparities at high frequencies and noted that the percept was not always spontaneously obvious to a naïve listener but often required the visual anchor of a concurrent oscilloscopic display. Moreover, the percept faded after a period of listening and required a restorative break before returning to salience. Even in frequency regions conducive to binaural beat perception (e.g., 500-Hz region, $\Delta f < 2$ Hz) it has been reported that the percept can fade after several minutes of continuous listening (Fritze, 1985). Training and experience also appear to play a role. For example, Stewart (1917) noted that when tones from slightly mismatched tuning forks were presented to each ear, 17 of 23 naïve listeners reported hearing beats after listening for a few minutes, but that “all experienced observers can hear them.” Wever (1949) also suggested that “a course of special training” would result in all listeners perceiving binaural beats. Thus, there is at least anecdotal evidence that the perception of binaural beats is not obligatory and, even when present, can be labile.

The physiological basis for binaural beats generated by pairs of frequency-disparate tones is usually attributed to the processing of interaural phase differences (IPDs) by binaurally sensitive neurons having preferred IPDs. For example, Kuwada et al. (1979) demonstrated that cells in the inferior colliculus respond cyclically to the periodic, dynamic changes in interaural phase associated with binaural beat stimuli. Interestingly, this ability of cells in the midbrain to follow dynamic IPDs is intact for binaural beat rates ($\Delta f$s) an order of magnitude or more greater than the frequency limit that has often been associated with human sensitivity to dynamic interaural differences, which is usually placed at a few Hz (e.g., Grantham and Wightman, 1978). This apparent dichotomy has led to efforts to reconcile the ‘binaural sluggishness’ of human behavioral performance with the physiological limits of binaural processing (Fitzpatrick et al., 2009). As will be seen, the results of the present study are relevant to this issue. The notion that the mechanism underlying the binaural beat percept reflects a sensitivity to dynamic IPDs necessarily requires that the percept be restricted to frequency regions where neural phase locking is intact. Although this does not exclude phase locking to the envelope of a stimulus, Bernstein and Trahiotis (1996) have demonstrated that the binaural beat percept carried by the envelopes of high-frequency stimuli, as reported by McFadden and Pasanen (1975), is likely to be due to sensitivity to dynamic interaural level differences (ILDs) and not strictly to IPDs. Stimuli in the present study are restricted to lower frequencies where neural synchrony is presumed to be robust.

In summary, there is now general concurrence on the optimum conditions necessary to generate a binaural beat percept, and an increased understanding of the neurophysiological basis for the percept. However, given the reports of individual variability and response lability, little attention has been paid to the issue of binaural beat salience. The purpose of this study, therefore, was to gauge the strength of the binaural beat percept by comparing the perceptual salience of binaural beats to that of another stimulus that is perceived to fluctuate, a sinusoidally amplitude-modulated (SAM) tone. Specifically, the study compared rate discrimination across the two classes of perceived fluctuation. The intent was to provide insights into the salience of binaural beats that, in turn, could contribute to an understanding of the lability of the percept. The study was framed as a sequence of three experiments: experiment 1 measured the just noticeable difference (JND) for binaural beat rate as a function of standard rate; experiment 2 equated the salience of a variable-depth SAM tone to that of a binaural beat of the same rate; and experiment 3 measured the rate JND for both ‘salience-matched’ SAM and 100% SAM.

## 2. Experiment 1. Binaural beat rate discrimination

### 2.1. Method

#### 2.1.1. Stimuli

Stimuli to evoke binaural beats consisted of two pure tones, one presented to each ear. The pair of standard tones differed in frequency, $\Delta f$, by either 4, 8, 16, or 32 Hz yielding binaural beats at those rates. The tones were 1250 ms in duration, corresponding to five cycles of 4-Hz modulation, and included 25-ms raised cosine onset/offset ramps. For each observation interval of a cued 2-alternative, forced-choice (2AFC) trial, as described below, the frequencies of the two tones were resampled within the range 400–500 Hz. This frequency region was chosen because it supports the widest range of beat rates (Licklider et al., 1950; Perrott and Nelson, 1969). The rationale for the frequency rove was to prevent the listener from using monaural frequency cues to perform the discrimination task. The frequency rove was implemented for each interval by first randomly selecting the tone for the left ear within the range 400–500 Hz, with the proviso that this frequency be different from either of the left-ear frequencies drawn for the other two observation intervals in the same cued 2AFC trial. The tone for the right ear was then selected for that interval as having the prescribed $\Delta f$ relative to the left-ear tone to generate the designated binaural beat rate. The right-ear tone was randomly selected as being the prescribed $\Delta f$ above or below the left-ear tone. In the cue interval (interval 1), and one of the subsequent two observation intervals at random, this $\Delta f$ corresponded to the standard beat frequency for that condition (4, 8, 16, or 32 Hz). In the third interval, the $\Delta f$ was larger (i.e., resulting in a higher beat rate). The starting phase for all tones was random on a presentation-by-presentation basis. The pure tones were presented at a level of 65 dB SPL. In addition, a Gaussian noise band passed from 2000 to 5000 Hz was continuously present at a pressure spectrum level of 30 dB/Hz. The purpose of the noise was to provide a limit of upward spread of excitation. Independent Gaussian noises were presented to each ear. The stimuli were delivered to the listener through Etymotic Research ER2 insert phones.

#### 2.1.2. Procedure

The listener’s task was to select the observation interval (interval 2 or 3) that was higher in beat rate than the cue interval. The procedure incorporated a 3-down, 1-up stepping rule that converged on the 79.4% correct point on the psychometric function. The initial step size was 0.25 in units of $\log(\Delta f_m/f_m)$, where $f_m$ designates the standard binaural beat rate. After 2 reversals in rate direction, the step size was halved to its final value of 0.125. The track was terminated after 8 reversals, and the geometric mean of the final 6 reversal rates was taken as the estimate of discrimination threshold for that track. At least three replications of threshold were collected for each standard binaural beat rate, and the geometric mean of all estimates was taken as the final threshold value, designated as the JND.

#### 2.1.3. Observers

Twelve normal-hearing adults (7 female) participated in this study.[1] The observers ranged in age from 20 to 57 yrs (median = 26.5 yrs) and had audiometric thresholds ≤ 20 dB HL across the octave frequencies 250–8000 Hz.

### 2.2. Results & discussion

The 12 observers provided similar data that are well described by the group mean. These mean discrimination thresholds are displayed as filled circles in Fig. 1 with error bars extending to the mean + 1 standard deviation as computed on $\Delta f$ in Hz. (This figure also contains data from experiment 3 to be discussed later.) Panel A plots the binaural beat frequency that was just noticeably different from the standard beat frequency as a function of the standard frequency. Panel B plots the results expressed as Weber fractions ($\Delta f_m/f_m$). A repeated-measures analysis of variance (ANOVA) on the Weber fraction data indicated a significant effect of standard beat rate ($F(3,33) = 2.965$; $p = 0.046$). Pairwise linear contrasts indicated that this was due to a significant difference between the Weber fractions at 4 Hz and 8 Hz ($F(1,11) = 10.498$; $p = 0.008$); none of the other pairs of rates differed ($p > 0.05$). This result indicates that the Weber fraction is slightly larger at 4 Hz than at higher rates, but that it is otherwise roughly constant for beat frequencies up to 32 Hz.

It is unclear what accounts for the slight threshold elevation at 4 Hz. One possibility is that it reflects the smaller number of fluctuation cycles available in the 1250-ms stimulus relative to the higher rates. The ability to discriminate binaural beat rates as high as 32 Hz appears, at first sight, to be at odds with earlier studies that put the upper limit of binaural temporal processing at about 5 Hz (Grantham and Wightman, 1978). However, more recent work using broadband 'phase-warp' stimuli has established that binaural temporal processing can be shown to be as sensitive as monaural temporal processing (Siveke et al., 2008).

One listener reported that the formation of the beat percept required more 'synthetic effort' at the highest rates presented. That is, when the frequencies of the two tones differed markedly, it was possible to listen to them 'analytically' as disparate steady tones in each ear rather than as a fused beat percept. It is not clear whether a fused image is necessary for the perception of binaural beats. On the one hand, Perrott (1970) demonstrated that binaural beats could occur independently of whether the dichotic tones were perceived as a fused image. On the other hand, in an electrophysiological study of binaural beats, Schwarz and Taylor (2005) noted that when musically trained observers attempted to assign musical intervals to the two tones across ears (presumably necessitating analytic listening) their binaural beat response diminished.

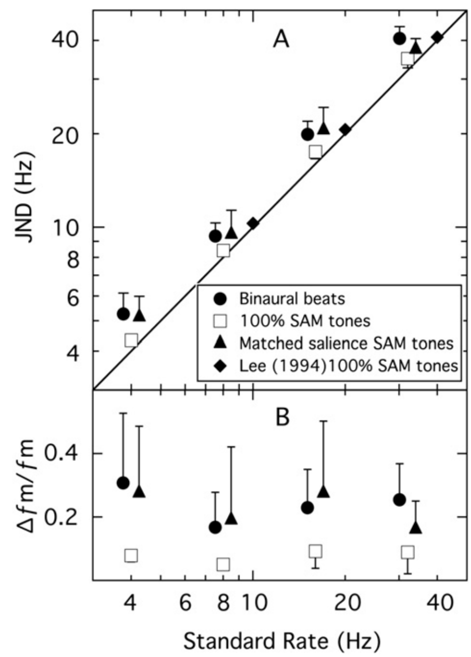


**Fig. 1.** Rate discrimination as a function of standard rate. Panel A: Just Noticeable Difference (JND) as a function of standard rate. Panel B: Weber fraction as a function of standard rate. Filled circles show binaural beat data from experiment 1; filled triangles (matched salience SAM tones) and open squares (100% SAM tones) show data from experiment 3. Filled diamonds in Panel A show data from Lee (1994).

In summary, binaural beat rate discrimination performance was relatively similar across listeners in this experiment for rates of 4–32 Hz. However, it is not clear that the salience of the binaural beat was equivalent across listeners. In order to assess beat salience, the goal of experiment 2 was to match the 'modulation salience' of SAM tones to binaural beats of the same rate.

## 3. Experiment 2. Salience of binaural beats vs. SAM tones

The purpose of this experiment was to match the modulation salience of the binaural beat to a SAM tone of the same modulation rate as the binaural beat but with an adjustable depth of modulation. That is, the task determined the depth of modulation of a SAM tone that resulted in a modulation percept that had similar strength – or salience – to that of the binaural beat. This approach has been used before for low rates of binaural beats (2–6 Hz), where the predominant percept is one of loudness fluctuation (Rutschmann and Rubinstein, 1965).

### 3.1. Method

#### 3.1.1. Stimuli

As in experiment 1, the binaural beat stimuli consisted of pairs of tones with $\Delta f$s of 4, 8, 16, or 32 Hz. However, no frequency rove was incorporated, and the tone pairs were always symmetric around 500 Hz. The SAM tone stimulus, presented diotically, had a carrier frequency of 500 Hz, and this carrier was modulated by a DC-shifted sine wave of 4, 8, 16 or 32 Hz. The depth of modulation was defined in units of $20\log(m)$, where $m$ is the modulation index (0–1). All stimuli were 1250 ms in duration, including

[1] A thirteenth observer was recruited for the study but exhibited unreliable performance, providing variable data with means that were usually three or more standard deviations above those of the other listeners. The poor performance did not appear to be due to particular difficulty perceiving binaural beats because the variable and elevated performance occurred for both binaural beat and SAM rate discrimination. This observer was excused from the study.

25-ms raised cosine rise/fall ramps. The starting phases of all tones, including the modulator, were randomly selected on a presentation-by-presentation basis, and the tones were presented at a level of 65 dB SPL. As in experiment 1, a Gaussian noise bandpassed from 2000 to 5000 Hz was continuously present at a pressure spectrum level of 30 dB/Hz with an independent noise presented to each ear.

### 3.1.2. Procedure

The matching procedure used of a series of 3-interval trials. In each trial a standard binaural beat stimulus was presented in intervals 1 and 3, while in interval 2 a SAM tone of the same modulation rate and duration as the binaural beat stimulus was presented. (Although the same standard tone frequencies were presented in intervals 1 and 3 for the binaural beat, the ear of presentation for each tone was reversed across these two intervals.) The observer's task was to vary the depth of modulation of the AM tone until the salience of modulation was judged to be equivalent to that of the binaural beat. The procedure made use of a graphical user interface wherein the three listening intervals of a trial were successively indicated on the monitor. After listening to the three intervals, the observer selected from an array of five adjustment options to determine the AM depth settings for the next trial, or else indicated that a match had been achieved. The five adjustment options were: (1) a coarse, or (2) a fine, reduction in modulation depth, (3) a coarse, or (4) a fine, increase in modulation depth, and (5) no adjustment (i.e., no change in modulation depth). The coarse and fine steps were 4 dB and 1 dB, respectively, in units of 20 log($m$). The option for no adjustment allowed the observer to repeat the trial at the same AM depth setting. There was no constraint on the number of trials an observer could listen to before selecting a match. For each modulation frequency (4, 8, 16, and 32 Hz), at least 3 – but as many as 5 – match estimates were obtained. The final match was taken as the average modulation depth of the SAM tone across all match estimates for that beat rate. The match estimates were blocked by modulation frequency, but the order of modulation frequency was random across observers. The starting AM depth across runs was not fixed but was arbitrarily selected to begin above or below the expected matching depth; i.e., with an initial modulation salience that was either robust or very weak.

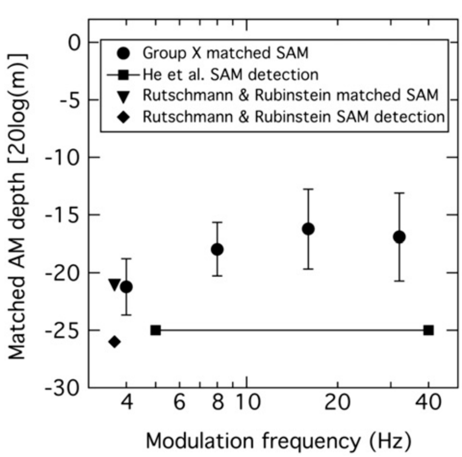


**Fig. 2.** Depth of modulation of SAM tones matched in salience to binaural beats as a function of beat rate. Circles show data from experiment 2. Squares show SAM detection data from He et al. (2008) and the inverted triangle and diamond show 4-Hz data from Rutschmann and Rubinstein (1965). See text for description. The latter data have been slightly offset for better viewing.

### 3.2. Results and discussion

The performance of the 12 listeners was relatively similar and is well represented by the group means. These are plotted in Fig. 2 as filled circles ±1 standard deviation. A repeated-measures ANOVA indicated that there was an overall effect of frequency ($F(3,33) = 7.552$; $p = 0.001$), and pairwise linear contrasts revealed that the AM depth at 4 Hz was significantly lower than for any of the other modulation rates ($F(1,11) = 11.177–20.661$; $p < 0.01$). Also shown in Fig. 2 (filled squares) are data from He et al. (2008) for AM detection thresholds in young, normal-hearing adults for 5-Hz and 40-Hz SAM, carried by a 500-Hz pure tone. This comparison shows that the AM depth required for matching modulation salience of binaural beats was relatively shallow and, at least for the 4-Hz rate, was not greatly above absolute detection threshold. It is informative to relate the 4-Hz findings from experiments 1 and 2: In experiment 1, rate discrimination was poorer at 4 Hz than at higher rates; in experiment 2 the salience of the 4-Hz beat was lower than at higher rates. This suggests that poorer rate discrimination might be associated with lower salience – a point revisited in experiment 3.

Rutschmann and Rubinstein (1965) also measured the SAM depth required for subjective equality with binaural beats in terms of loudness fluctuation. They tested predominantly in the 300-Hz region using beat rates ($\Delta f$s) of 2–6 Hz, where the primary beat percept is one of loudness fluctuation. They were particularly interested in effects at low sensation level (SL) and did not test above 30 dB SL. (For comparison, the 65 dB SPL tones used in this experiment were, on average, at about 55 dB SL.) They also measured SAM detection thresholds for their stimuli. The results of their descriptive study showed notable effects of both SL and frequency region. As SL decreased, the SAM depth required for both detection and perceptual equivalence with binaural beats increased, but not in parallel. Relatively greater increases in SAM depth were required for perceptual equivalence at low SLs than for SAM detection. However, the interesting finding in the context of the present experiment concerned the frequency effect. For tone pairs with $\Delta f = 4$ Hz in either the 150-Hz or 300-Hz region, and at the highest level tested (30 dB SL), the median SAM depth that gave perceptual equivalence to the corresponding binaural beat was about −13.5 dB, well above their measured SAM detection threshold of about −26 dB for the same stimuli. However, when the frequency region was shifted to 600 Hz, the median SAM depth for perceptual equivalence dropped to about −20.9 dB, whereas the SAM detection threshold remained constant at about −26 dB. Thus, it appears that the salience of the 4-Hz binaural beat diminished as the frequency region increased from 300 Hz to 600 Hz. In the present experiment, where the frequency region was restricted to 500 Hz, the SAM depth for perceptual equivalence for $\Delta f = 4$ Hz was, on average, −21.2 dB. This corresponds closely to the −20.9 dB depth measured by Rutschmann and Rubinstein (1965) at 600 Hz for the same $\Delta f$ despite notable stimulus differences; in particular, their presentation level was lower and their modulator phase for the SAM stimuli was inverted across ears. This close correspondence is highlighted in Fig. 2 by including both the SAM depth at matched salience (inverted triangle) and SAM detection threshold (diamond) for $\Delta f = 4$ Hz in the 600-Hz region from the Rutschmann and Rubinstein study. Note also the close correspondence of their detection threshold to those measured by He et al. (2008).

The only other published report that we are aware of involving a comparison of binaural beats and SAM is that of Groen (1964), who compared the loudness modulation associated with low rate binaural beats to monaural SAM and concluded that the loudness modulation corresponded to about a 2-dB fluctuation. Although stimulus details are largely absent in that summary report, it can be surmised that the beat rate was probably about 3 Hz, and that the presentation level was about 60 dB SPL. A SAM tone with a peak-to-dip fluctuation of 2 dB translates to a modulation depth of about −18.8 dB (i.e., $m \approx 0.1146$). However, it is difficult to relate this depth to any particular frequency region since Groen (1964) referred to the 2-dB loudness modulation as holding across the range 90–800 Hz. The results of Rutschmann and Rubinstein (1965) suggest that the modulation depth at perceptual equivalence should vary across this range. Nevertheless, the single value of −18.8 dB derived from Groen (1964) does fall within the range of frequency-dependent depths reported by Rutschmann and Rubinstein (1965).

In summary, the results of this study, along with those of Rutschmann and Rubinstein (1965), suggest that the modulation salience of binaural beats is relatively weak, at least in the 500-Hz region. This low modulation salience raises the question of whether the beat rate discrimination measured in experiment 1 was limited by modulation salience. In other words, is there is an association between performance on a binaural beat discrimination task and the perceptual salience of those beats? In order to address this question, experiment 3 measured SAM rate discrimination at the modulation depths associated with matched salience.

## 4. Experiment 3. SAM rate discrimination

The purpose of this experiment was to measure modulation rate discrimination for SAM tones having modulation depths set to the 'matched salience' depth measured in experiment 2. For reference, rate discrimination was also measured for 100%-modulated SAM tones.

### 4.1. Method

The diotic SAM stimuli were the same as those used in experiment 2. For the matched salience condition, the depth of modulation for a particular rate was set to each individual listener's salience match, as measured in experiment 2. For the reference condition, the depth of modulation was set to 100%. In order to give the discrimination procedure some limited pitch rove, not unlike that used in experiment 1 to minimize monaural frequency cues, the SAM tone carrier frequency was randomly varied within the range 440–460 Hz on a presentation-by-presentation basis. This more circumscribed frequency range, relative to the 400–500 Hz range used in experiment 1, was dictated by the desire to keep the modulation sidebands within that same 100-Hz range. That is, it was estimated that an upper bound for SAM rate would be about 40-Hz (for discrimination relative to a standard 32-Hz SAM), and therefore the lower sideband would be at 400 Hz for a 440-Hz carrier, whereas the upper sideband would be at 500 Hz for a 460-Hz carrier. This more constrained carrier frequency rove therefore kept all stimulus components within the range 400–500 Hz, coincident with the frequency range implemented in experiment 1. As in the previous experiments, the presentation level for each SAM tone was 65 dB SPL, and a Gaussian noise bandpassed from 2000 to 5000 Hz was continuously present at a pressure spectrum level of 30 dB/Hz, with an independent noise presented to each ear. The same cued 2AFC procedure was used as in experiment 1, and the computation of stepsize was also the same.

### 4.2. Results and discussion

Dealing first with the reference 100% SAM depth, discrimination performance was relatively similar across the 12 listeners and is well represented by the mean. The mean JNDs are shown in Fig. 1 as open squares with downward error bars extending to the mean-1 standard deviation. Also shown as filled diamonds are data from Lee (1994) for rate discrimination of 500-Hz SAM tones modulated at 100%. In general, rate discrimination for 100% SAM is a constant proportion of standard rate, at least for standard rates below about 40 Hz. The average Weber fraction across the four standard rates in this study was 0.08. This is higher than the 0.03 measured by Lee (1994).

For the matched salience SAM stimuli, the performance of all listeners was somewhat poorer than for the 100% SAM stimuli. The mean JNDs and corresponding Weber fractions are displayed in Fig. 1 as filled triangles, with the error bars extending to the mean + 1 standard deviation.[2] The main question of interest was how rate discrimination compared across the three sets of stimuli: 100% SAM, matched salience SAM, and binaural beats. To assess this, a repeated-measures ANOVA was undertaken on the three sets of Weber fraction data (Fig. 1, Panel B). The analysis indicated a significant effect of stimulus type ($F[2,20] = 15.127$; $p < 0.001$) but no effect of standard modulation rate ($F[3,30] = 2.40$; $p = 0.087$). The interaction between stimulus type and modulation rate was also not significant ($F[6,60] = 1.179$; $p = 0.329$). Planned comparisons showed that at each standard modulation rate, the Weber fraction for the 100% SAM was smaller than that for the matched salience SAM and the binaural beat. The only exception to this pattern was at the 8-Hz rate, where the difference between the matched salience SAM and the 100% SAM approached, but did not reach, significance ($p = 0.06$). In contrast, the Weber fractions for the matched salience SAM and the binaural beat generally did not differ. The only exception to this pattern was at the 32-Hz rate where the Weber fraction for the matched salience SAM was significantly smaller than for the binaural beat ($p = 0.03$). The general pattern of results, therefore, indicates that modulation discrimination performance was similar between stimuli matched for modulation salience (binaural beats and low-depth SAM), but that this performance was poorer than for 100% SAM.

## 5. Conclusion and summary

The purpose of this study was to assess the strength of the binaural beat percept by comparing rate discrimination for binaural beats to that for SAM tones. The results indicated that, for the frequency region and rates tested here, the Weber fraction for binaural beat rate discrimination is constant, at least for rates above 4 Hz. Rate discrimination for SAM tones is also independent of base rate in this region. More importantly, discrimination acuity for binaural beats is similar to that for SAM tones whose depths of modulation have been adjusted to provide equivalent modulation salience. Because these matched salience SAM tones had relatively shallow depths of modulation, it can be surmised that the perceptual strength of binaural beats is relatively weak. Despite this weakness, all the observers in this study were able to perceive binaural beats, and the perceptual strength of these beats was relatively similar across listeners – as judged by the similarity in depths of their matched salience SAM tones. This uniformity across listeners contrasts with early reports noting that some listeners cannot perceive binaural beats (e.g., Wever, 1949). Presumably this

[2] One observer, who was otherwise a reliable listener throughout the study, provided unexpectedly extreme thresholds at the two lowest modulation rates. These two aberrant thresholds were greater than 4 standard deviations above the mean for the other listeners. This threshold elevation was not associated with exceptionally shallow SAM depths at matched salience, as the depths for this observer were consistent with those of the other observers. Unfortunately, this observer was unavailable to return for confirmatory testing of these suspect points and so these data points were treated as outliers and not included in the analysis.

disparity reflects, to some extent, methodological differences (Tobias, 1963).

Two important caveats should be noted. First, the findings of this study are restricted to a single frequency region (400–500 Hz). The work of Rutschmann and Rubinstein (1965) indicates that the salience of binaural beats – as gauged by the modulation depths of matched SAM tones – increases as the frequency region of the dichotic tones decreases. The 400–500 Hz region tested here likely gives rise to lower salience binaural beats than the 150–300 Hz region tested in their study. Thus, the findings of the present study might not generalize to other frequency regions. The second caveat is that the present findings on the salience of binaural beats might not generalize to other binaural beat rates. In particular, it is known that the binaural beat percept disappears for larger $\Delta f$s (Licklider et al., 1950). For most of the binaural beat range tested here (8–32 Hz), it is notable that the modulation depth at matched salience for SAM tones remained relatively constant. However, the results of Dietz et al. (2008) suggest a decline in salience over this range. They measured binaural beat detection for wide-band ('phase-warped') stimuli by adjusting binaural modulation depth as a function of beat rate. The binaural modulation depth was adjusted by mixing the phase-warped stimulus with binaurally uncorrelated noise in different ratios. They found that the binaural modulation depth at detection threshold increased monotonically over the beat range 10–75 Hz. One interpretation of this result is that binaural beats are more salient at lower than at higher beat frequencies for some stimuli even within the range tested in the present study. Taken together, findings concerning the strength of the binaural beat percept likely depend in part on the frequency region tested, the beat rate tested, and the type of stimulus tested.

In conclusion, this study found that the strength of the binaural beat percept was relatively weak for $\Delta f$s of 4–32 Hz in the 400–500 Hz region, as gauged by the modulation depth of matched salience SAM tones. The Weber fraction for binaural beat rate discrimination was constant, at least for rates above 4 Hz, and compared well with that measured for matched salience SAM tones. For the range of $\Delta f$s tested here it is likely that the predominant percept is one of loudness fluctuation, transitioning to roughness; i.e., this $\Delta f$ range likely exceeds that associated with a robust sense of intracranial motion. If the concept of binaural sluggishness is restricted to paradigms that require the detection of spatial or intracranial motion, then the ability to perform binaural rate discrimination as high as 32 Hz supports the notion that binaural processing, *per se*, is not necessarily sluggish. A notable finding was that binaural beats were perceived by all listeners. This suggests that earlier reports of individual variability in perceiving binaural beats might be a reflection of the measurement procedure rather than the veridicality of the percept itself.

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