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No Unified Scales for Perceptual Magnitudes: Evidence from Loudness

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Abstract

In this article we consider whether perceptual magnitudes are represents on unified underlying scales. We exploit the ubiquitous sequential effects seen in judgments concerning the attributes of simple perceptual stimuli. Participants made judgments about the intensity of sinusoidal tones and white noise hisses. On each trial in Experiment 1, participants heard a tone and a hiss and judged which was the louder. The loudness of a stimulus was assimilated much more towards a stimulus of the same type on the previous trial, compared to a stimulus of the other type. In Experiment 2, the effect of the stimulus on the previous trial in an absolute identification of loudness task was larger when previous and current stimuli were of the same type. The attenuation of sequential effects by a switch of stimulus types suggests that the loudness of tones is not represented in the same way as the loudness of hisses. We argue that these sequential effects are indicative of the relativity of perceptual judgment.

The experiments in this article were designed to address two questions about the representation of simple perceptual stimuli. First, are perceptual magnitudes represented on the same underlying, unified psychological scale or dimension? An alternative way of framing this question is to ask whether stimulus attributes can be abstracted from one another and represented independently. Second, are stimulus attributes judged according to their absolute magnitudes or judged relative to other recent or contextual stimuli? Both of these issues have received some attention in the literature. Here we introduce two new experimental procedures that reexamine these questions.

Integrality and Separability

For some pairs of psychological dimensions, judgment of the level of a stimulus on one dimension is not interfered with by irrelevant variation on another dimension. Such dimensions are said to be separable. For other pairs of dimensions, orthogonal variation on one dimension interferes with judgments of the level of a stimulus on the other dimension. Such dimensions are said to be integral. It seems that, for integral stimuli, stimulus attributes are not represented independently of one another.

A classic example of these phenomenon is the Garner and Felfoldy (1970) card sorting task. Participants sorted stimuli presented on cards on the basis of one dimension. Within the set of cards to be sorted, the level of the stimulus on another dimension was either held constant, varied in a correlated way, or varied in an orthogonal way. When sorting stimuli that were either single Munsell colour chips that could vary in value and chroma, or dots that could vary in horizontal and vertical position, facilitation was seen in the correlated condition and interference in the orthogonal condition. However other dimension pairs (the value and chroma of separate Munsell colour chips; circle size and diameter angle) showed little or no facilitation or interference in these conditions. Garner and Felfoldy noted that in direct stimulus scaling studies, for the dimension pairs they tested, integral stimuli gave a Euclidean metric and separable stimuli gave a city-block metric thus building a relationship between two previously disparate concepts. Considerable empirical and theoretical work has been done in this area - most notably with the distinction between perceptual and decisional separability by Ashby and his collegues (see, e.g., Ashby & Maddox, 1994; Ashby & Townsend, 1986) - but the basic concepts of integral and separable dimension pairs remain.

In both of the experiments we present in this article, we will demonstrate a different, but related phenomenon. However, before introducing these experiments we review evidence of the rather ubiquitous sequential effects seen in many psychophysical tasks.

Sequential Effects in Psychophysics

The enterprise of psychophysics sought to find a lawful relationship between physical stimulus intensity and the psychological percept of the stimulus. The enterprise began with Fechner's (1860/1966) law, which relates the physical stimulus intensity to the psychological sensation of the stimulus using the logarithm transform. Almost 100 years later, Stevens (1957) showed that direct judgments of stimulus magnitudes conformed better with a power law. Both of these laws have in common the idea that representation is absolute: the percept of a stimulus's magnitude is based on its physical intensity.

In many psychophysical tasks, judgments of a stimulus's magnitude are strongly influenced by either the stimuli or responses from immediately preceding trials. Baird, Green, and Luce (1980) demonstrated that two-thirds of the variability in loudness estimates was explained by the variability in the previous estimate when loudnesses were similar. In absolute identification tasks, where participants are typically asked to respond to stimuli with the rank of their magnitude, responses are typically biased towards the immediately preceding stimulus (assimilation: see, e.g., Garner, 1953; Holland & Lockhead, 1968; Long, 1937; Luce, Nosofsky, Green, & Smith, 1982; Stewart, 2001; Ward & Lockhead, 1970, 1971). Assimilation to preceding items is also observed in magnitude estimation tasks (e.g., Jesteadt, Luce, & Green, 1977), in matching tasks (Stevens, 1975, p. 275), and in relative intensity judgment tasks (Lockhead & King, 1983).

Authors differ in their accounts of these sequential effects. Some authors dismiss these effects as biases of absolute judgment. For example, Stevens is careful to randomize the order of stimulus presentation and then average across many trials in obtaining his power law data, thus ignoring sequential effects present in his data. Others view the biases as a consequence of memory processes (e.g., Holland & Lockhead, 1968; Lockhead & King, 1983) or as attentional processes (e.g., Luce, Green, & Weber, 1976) or decision processes (e.g., Treisman, 1985) operating within a modified Thurstonian framework. An alternative is that these sequential effects are revealing the basis of absolute judgments: that stimuli are judged relative to recent stimuli (see, e.g., Helson, 1964; Laming, 1997; Stewart, Brown, & Chater, 2002). This is an idea that we return to in the General Discussion.

Experiment 1

The intuition motivating Experiment 1 is that there are no common scales for basic psychophysical properties such as loudness, brightness, and weight. Instead, the idea is that stimulus attributes are not abstracted from one another. Under such a hypothesis the loudness of pure sinusoidal tones, for example, would not be represented in the same way as the loudness of white noise stimuli.

On each trial in Experiment 1, participants were presented with two stimuli: a pure sinusoidal tone and a white noise hiss. Participants' task was to decide which stimulus was the louder of the two. We examined the sequential effects caused by the immediately preceding trial. In absolute identification and magnitude estimation, the current stimulus is typically assimilated towards the previous stimulus. For example, a moderate stimulus is judged quieter after a quiet stimulus and louder after a loud stimulus. If the absolute magnitude of the intensity of tones and hisses is represented on a common scale, then the tone and the hiss should both be affected in the same way by the tone and the hiss from the previous trial. Alternatively, if the loudness of tones is represented at least partially independently from the loudness of the hiss, then the tone should be assimilated towards the tone on the previous trial and the hiss should be assimilated towards the previous hiss.

Method

Participants Thirty two students from the University of Warwick participated for payment.

Stimuli Two sets of seven stimuli were constructed: 512-Hz sine wave tones and white noise hiss sounds. The stimuli were generated using Mathematica 4.2 software and stored on a PC in WAV file format with a sample depth of 16 bits and a sample rate of 44100 Hz. The amplitudes were selected carefully to avoid possible artifacts due to sample rate and depth during digital sampling. All stimuli had a duration of 500 ms. The amplitude of stimuli was linearly ramped from zero to maximum in the first 50 ms of the stimulus and from maximum to zero in the last 50 ms of the stimulus to prevent click artifacts at the stimulus onset and offset. Stimuli were transduced using a Creative Labs Ensoniq CT5880 audio PCI sound card and Sennheiser eH2270 headphones. The loudnesses of the tones were 72.0, 78.0, 82.0, 84.5, 87.0, 89.0, and 90.0 dB, and the loudnesses of the hisses were 60.0, 64.0, 70.0, 72.0, 74.0, 76.0, and 78.0 dB. These values were selected so that tones and hisses of equal rank sounded approximately equally loud, although this assumption is not crucial to the design.

Design Each trial consisted of a tone and a hiss. The experimental trial pairs comprise T4 and H4 preceded by either T1 and H7 or T7 and H1. Under the hypothesis that a stimulus is assimilated towards the stimulus of the same type from the preceding trial, T4 should seem quieter when it follows T1 and louder when it follows T7. Similarly, H4 should seem quieter when it follows H1 and louder when it follows H7. Thus when comparing the loudness of T4 and H4 on the last trial in any experimental pair, T4 should be judged louder than H4 when the preceding trial contains stimuli T7 and H1. Alternatively, T4 should be judged quieter than H4 when the preceding trial contains stimuli T1 and H7.

The design also included control trial pairs. These pairs differ from the experimental pairs in that the stimuli on the first trial in the pair both have the same rank loudness. Following the assimilation argument outlined for the experimental trial pairs leads to the prediction that, on the last trial in any control pair, T4 and H4 should seem equally loud. The allocation of tones to ears was counterbalanced.

Participants experienced six blocks of 112 trials. Together, the experimental and control trials number 32. These trials were placed at random in the sequence of 112 trials, with the constraint that the pairs of trials must remain consecutive. The remaining trials were deemed filler trials. Stimuli were filled in at random in the left-ear and right-ear slots in each trial, with the constraint that within an entire block each stimulus appeared 16 times.

Procedure Participants were instructed that on each trial they would hear a tone in their left ear and a hiss in their right ear or vice versa, and that they were to judge which seemed louder to them. Each trial began with the two stimuli and a '?' prompt. Participants pressed key z, which was labeled 'T', to indicate that the tone was the louder of the pair, or key m, which was labeled 'H', to indicate that the hiss was the louder of the pair. After their response the '?' prompt was removed, and there was a 500-ms pause before the next trial began automatically. No feedback was given. The breaks between blocks were self timed by participants.

Results

Here we consider performance on the control and experimental trial pairs. On the last trial, trial *n*, in these pairs T4 and H4 were presented. On the experimental trials either T1 and H7 or T7 and H1 were presented on the previous trial, trial *n*-1. On the control trials either T1 and H1 or T7 and H7 were presented. The proportion of hiss responses on trial *n* is shown as a function of stimuli on trial *n*-1 in Figure 1.

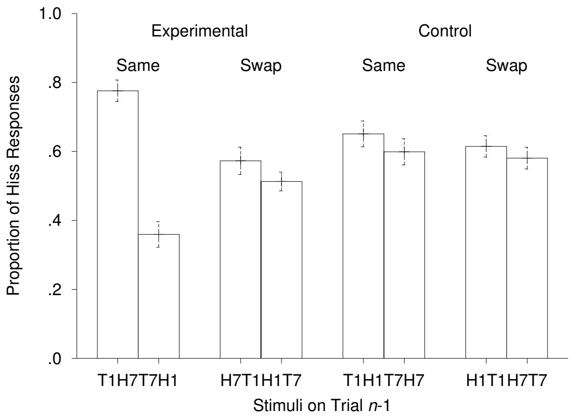

Figure 1: The proportion of hiss responses to stimuli T4H4 on trial *n*.

The leftmost two bars show the effect when the tone on trial *n* was presented to the same ear as the tone on trial *n*-1.The results are consistent with the assimilation of stimuli on trial *n* toward only stimuli of the same type on trial *n*-1. When the type of stimuli played in each ear was swapped (third and fourth bars), the effect was greatly attenuated, and no larger than on control trials (rightmost four bars). This pattern was confirmed by a three-way ANOVA (trial pair type: experimental or control x ear: same or swapped x stimuli on trial *n*-1). There was a significant main effect of trial pair type, $F(1, 31) = 8.79$, $p < .01$. There was no significant main effect of ear, $F(1, 31) = 1.62$, $p = .21$. There was a significant main effect of the stimuli on the previous trial, $F(1, 31) = 43.13$, $p < .01$. These effects were qualified by significant two-way interactions between trial pair type and the stimuli on trial *n*-1, $F(1, 31) = 21.31$, $p < .01$ and ear and stimuli on trial *n*-1, $F(1, 31) = 24.68$, $p < .01$. The remaining two-way interaction, trial pair type by ear, was not significant, $F(1, 31) = 0.01$, $p = .93$. The three-way interaction was significant, $F(1,31) = 21.27$, $p < .01$, showing that the assimilation effect only occurred for experimental pairs when the type of stimulus presented to each ears was constant across the trial pair.

Discussion

The results of Experiment 1 were as expected under the within-type assimilation hypothesis. If T4 and H4 were presented on trial *n*, the proportion of times the hiss was judged louder was higher when the preceding trial comprised T1 and H7, compared to T7 and H1. The loudness of the tone on trial *n* assimilates much more to the loudness of the tone on trial *n*-1 compared to the loudness of the hiss, and the loudness of the hiss on trial *n* assimilates much more to the loudness of the hiss on trial *n*-1 compared to the loudness of the tone.

This within-type assimilation effect only occurred when stimuli of the same type on consecutive trials were presented to the same ear. Thus, the locus of the within-type assimilation effect must occur early in the auditory pathway before information from the two ears is integrated (i.e., the cochlea nucleus), with only a very small contribution after (i.e., the superior olivary nulceus, the medial geniculate nucleus, or the auditory cortex).

Experiment 2

We designed Experiment 2 to investigate further the hypothesis that there are (at least partially) independent scales for representing the loudness of different types of stimuli using an alternate task. As described in the Introduction, in absolute identification tasks, stimuli are typically assimilated towards the previous stimulus. However, in these experiments stimuli only differed on the attribute that they were identified on. In Experiment 2, eight tones differing in loudness were identified along with eight hisses differing in loudness. We hypothesized that the magnitude of a stimulus would only be assimilated towards the previous stimulus when both stimuli were of the same type if the loudnesses were represented on different scales. Alternatively, if loudness is abstracted from the other attributes of the stimulus, then assimilation should not be attenuated when stimuli are of different types.

Method

Participants Twenty students from the University of Warwick participated in this experiment for payment.

Stimuli Two sets of eight stimuli were constructed as in Experiment 1. The loudnesses of the tones were 67.0, 74.0, 77.0, 80.0, 82.0, 84.0, 86.0, and 87.0 dB and the loudnesses of the hisses were 60.0, 64.0, 67.0, 69.0, 71.0, 73.0, 74.0, and 75.0 dB.

Procedure Participants were tested individually in a quiet room. Participants experienced six blocks of 80 stimuli. On each trial a stimulus was selected at random from the set of 16. On each trial the stimulus was played and accompanied by a '?' prompt on the screen until participants responded. Participants were free to respond from the onset of each tone using the number keys '1'-'8' along the top of a standard keyboard. Participants were instructed to press '1' for the quietest stimulus through to '8' for the loudest stimulus. The correct response (i.e., the rank of the amplitude of the stimulus within its own type) was displayed on the screen for 500 ms after the end of the tone or the response, whichever was later. There was a 500-ms blank screen before the next trial began automatically. The breaks between blocks were self timed by participants.

Results

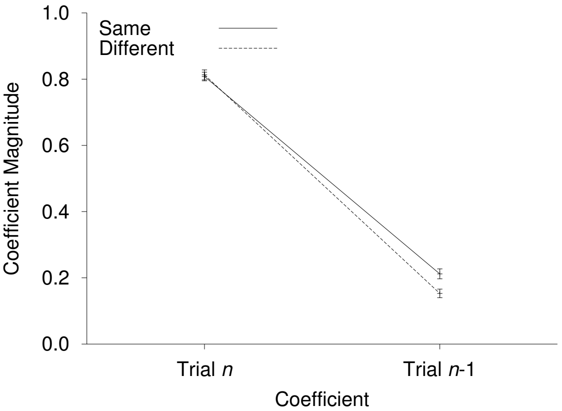

Figure 2: Regression coefficients for the current and previous stimuli when predicting the current response.

The sequential effects were examined by fitting four linear regression models to the data from each participant. Specifically, the response on trial *n* was predicted as a function of the stimulus on trial *n*-1 and the stimulus on trial *n*. The four fits corresponded to the four different possible combinations of trial pairs: TT, HH, TH, and HT. Coefficients were averaged across trials where the stimuli on trials *n*-1 and *n* were the same, and trials where the stimuli on trials *n*-1 and *n* were different. The coefficients for trial *n*-1 and trial *n* are shown in Figure 2. The large coefficients (approaching 1) for the stimuli on the current trial show that the current stimulus is a strong predictor of the current response. The smaller positive coefficients for the previous stimuli show that there is an assimilation effect: The current response is biased towards the previous stimulus. A two-way ANOVA (the same or different stimuli on trials *n*-1 and *n* x coefficient for the stimulus on trial *n*-1 or trial *n*) was run. The effect of the stimulus on the current trial was significantly larger than the effect of the stimulus on the previous trial, *F*(1, 19) = 910.62, *p* < .0001 (η2 = .98). The effects of the previous and current stimuli were smaller if they were of different types, *F*(1, 19) = 12.25, *p* < .0001 (η2 = .87). Finally - and of most interest to the current hypothesis - the drop in coefficient between the current and previous trial was larger if the stimuli on those trials were different, *F*(1, 19) = 12.12, *p* = .0025, (η2 = .39). Two planned *t* tests demonstrated that the effect of the current stimulus was not significantly smaller when the previous and current stimuli were of different types, *t*(19) = 0.46, *p* = .6480 (a difference of .03 can be detected with 80% power), and that the effect of the previous stimulus was significantly smaller when the previous and current stimuli were of different types, *t*(19) = 4.83, *p* = .0001 (η2 = .55).

The accuracy on trial *n* was also examined as a function of the type of stimuli on trials *n* and *n*-1. The proportion of correct responses on trial *n* was significantly higher when the previous stimulus was of the same type as the current stimulus (mean = .36, SE = .01) compared with the case where the types differed (mean = .34, SE = .01), t(19) = 2.25, p = .0364 (η^2 = .20).

Discussion

The assimilative effect of the previous stimulus on the current stimulus was significantly attenuated when the current and previous stimuli were of different types compared with when the current and previous stimuli were of the same type. This is consistent with the hypothesis that the representation of the loudness of tones is qualitatively different from the representation of the loudness of hisses. Although sequential effects were larger on tone-tone or hiss-hiss trial pairs, accuracy was also higher on the last trial in these pairs compared with tone-hiss and hiss-tone pairs. In the Introduction we described two different interpretations of sequential effects. Under one interpretation, absolute magnitudes of stimulus properties are assumed to form the basis of judgments, and sequential effects are viewed as some kind of bias on these judgments. If this view is correct, then it is not clear how a reduction in sequential effects on a switch of stimulus type, and thus a reduction in the bias, can lead to decreased accuracy: Surely a removal of bias should increase accuracy? Instead we feel that these data sit more comfortably with the alternative interpretation: Sequential effects should be viewed as revealing the relativity of psychophysical judgment.

The data from Experiment 2 are consistent with the findings of Luce and Green (1978). Their task was a standard magnitude estimation task for tones differing in loudness. However, two different frequencies of tone were used (1 and 4 kHz). They obtained a high correlation between the previous and current responses when successive loudnesses were similar (consistent with Baird, Green, & Luce, 1980) that was attenuated when the previous and current stimuli were of different frequencies (reflecting our regression coefficients). Also, the coefficient of variation (the standard deviation divided by the mean) of the ratio of successive responses was smaller when the previous and current stimuli were of similar magnitude, and this reduction was abated when the previous and current stimuli differed in frequency (reflecting our accuracy data).

General Discussion

In Experiment 1, on each trial, participants were presented simultaneously with a tone and a hiss and asked to judge which was louder. The loudness of the tone on the current trial was assimilated towards the loudness of the tone on the previous trial. Independently, the loudness of the hiss on the current trial was assimilated towards the loudness of the hiss on the previous trial. In the absolute identification task in Experiment 2, the assimilation of the current stimulus towards the previous stimulus was attenuated when the current and previous stimuli were of different types, as was the accuracy of responding on the current trial. Together these data suggest that information about the loudness of a stimulus is not represented separately from the information about other stimulus attributes. If the information was represented separately then, for example, the effect of a tone or a hiss (of equal loudness) on the previous trial should have been the same. We suggest that there may not be a single underlying scale representing loudness independently of other stimulus attributes.

In the Introduction we described how, for integral dimension pairs, the level of a stimulus on one dimension can interfere with judgments concerning only the other dimension. It is as if dimensions which can be physically independently manipulated are psychologically fused: a within-stimulus effect. Our own data concern between-stimulus effects. A previous stimulus biases judgments of the level of a current stimulus on one dimension only if the stimuli are similar on other dimensions.

A Paradox?

Typically sequential effects in an absolute identification task are larger (in absolute terms) when stimuli differ more. For example, in a typical absolute identification experiment of 10 tones differing in frequency from our own lab (Stewart, Brown, & Chater, 2003) if Stimulus 10 was preceded by Stimulus 1, then the response to Stimulus 10 typically underestimated the stimulus by one point on the scale. If instead the preceding stimulus was Stimulus 5, then the underestimation was only half a point. Similar effects are seen in loudness identification (see, e.g., Ward & Lockhead, 1970, 1971). If these frequency and loudness effects are additive, then the maximal sequential effect should be given when the preceding stimulus differs in both frequency and loudness. However, our data and those of Luce and Green (1978) suggest that a change in frequency should attenuate the effect of the previous stimulus's loudness, and a change in loudness should attenuate the effect of the previous stimulus's frequency. An account of these sequential effects in terms of a confusion in memory would need to explain why only stimuli matching on all but the judgment dimension are confused, whilst simultaneously there is a larger effect if stimuli differ more on that dimension. We are not sure how to resolve this issue.

A Neural Population Code Hypothesis

Neurophysiological, anatomical and cognitive neuropsychological studies have provided a reasonable understanding of which sensory information is coded in which neural populations. For some attributes, such as the loudness and frequency of a tone, this information is coded within the same population: Signals in the same auditory fibers must be attended to deduce loudness and frequency information. Luce and Green (1978) proposed a neural attention hypothesis for auditory psychophysics. Under this hypothesis, a set of auditory fibers from the total population may be attended. Attention is assumed to be dwell on the fibers that were activated by recent stimuli. Thus if successive stimuli are similar, then the information contained in last stimulus in any similar pair will be attended to. If the successive stimuli are different, then attention will have been directed away from the last stimulus by the first stimulus. Using this hypothesis they provide an account their effects (described in the Discussion of Experiment 2). It may well be possible to use information about neural populations to make a priori predictions about novel dimension pairs that will and will not show effects of the sort we describe here. The existing evidence that some dimension pairs are integral and others separable suggests that our findings may be limited only to integral dimension pairs. Claims concerning generalization to other attributes must wait for demonstrations with other stimulus types.

Assimilation or Priming?

Traditionally, assimilative effects are accounted for by assuming that the representation of the current stimulus is confused with the previous stimulus. An alternative explanation of these data is that tones prime the perception of subsequent tones and hisses prime the perception of subsequent hisses. (We thank an anonymous reviewer for this suggestion.) Suppose loud stimuli prime more than quiet stimuli. Then, for example, T1 would only prime a little and T7 would prime a lot. Thus, T4 would seem louder after T7, when it was primed a lot, compared to T1, when it was only primed a little. Under this account, priming can account for the assimilation seen in Experiments 1 and

2. Whether it is priming during the perception of a stimulus that leads to a biased representation, or alternatively confusion with other representations, our central claim - that the loudness of a stimulus is not represented independently of other stimulus attributes - still stands.

The Relativity of Judgment

In our recent work (e.g., Stewart, Brown, & Chater, 2002, 2003) we have been pursuing the idea that absolute categorical judgments are relative (see also Laming, 1997). Stimuli seem to be judged relative to other simultaneous or recent contextual stimuli. The finding in Experiment 2 - that when sequential effects are attenuated by a change of stimulus type accuracy is significantly reduced rather than increased - would seem to be problematic for those accounts that suggest such sequential effects should be considered as a biasing of absolute judgment. A relative judgment account can accommodate these data: When there is a change in the stimulus type, removing at least part of the context used to make a relative judgment, then there will be a reduction in accuracy.

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