A New Illusion of Time Perception

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When two very short time intervals are presented serially by sound markers (in such a way that they share a common marker) the subject's duration judgments of the second time interval can be affected by the duration of the first interval. Such a conspicuous effect has not been reported in the literature. Standard empty time intervals of 120, 240, 480, and 720 msec were preceded by a neighboring empty time interval of various physical durations, and subjects adjusted a comparison empty time interval to the same subjective duration as these standards. We found clear underestimations of the standard duration when its physical duration was 120 msec. For example, when the preceding duration was 45 msec, the relative underestimation was about 40%. Because such a stable and remarkable underestimation appeared in a very simple situation, this phenomenon may be called a new illusion. Such an illusion did not appear when the time interval to be judged was succeeded by another time interval. At present we cannot explain the illusion, but in the general discussion we attempt to relate it to some findings in rhythm perception.

Introduction

ILLUSORY or paradoxical perceptions provide good clues to the mechanism of our perceptual system, as has been amply demonstrated in the study of visual perception. For auditory perception, there has been an upsurge in the reporting of illusions and paradoxes in the last two decades,

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thus elucidating the way the listener structures his auditory environment (e.g., Deutsch, 1986a).

In the field of music perception, various illusions of pitch and melody have been reported. Some well-known examples are the octave illusion, the scale illusion (e.g., Deutsch, 1975) and Shepard’s (1964) impossible figure of pitch circularity. In the field of time perception, however, only a few illusory phenomena have been reported in the literature. A classical example (Hall & Jastrow, 1886) is the illusion of a divided time interval: if an empty time interval bounded by two sound markers contains dividing markers, it sounds subjectively longer. Another, recently reported time illusion is the interaural tempo illusion: when a sequence of sounds alternates between the ears its subjective tempo is slower than that of the monaural counterpart (Axelrod, Guzy, & Diamond, 1968; ten Hoopen, Vos, and Dispa, 1982).

One of the reasons that more illusions have been found in the field of melody perception than in the field of time perception might be that larger auditory contexts were used in the study of melody perception. A clear example is the buildup of streaming by frequency: only after having heard a certain number of cycles alternating in frequency does one get the sensation of streaming, depending on tempo and frequency difference (e.g., Bregman, 1978). Although the effect of context in time perception or estimation has long been a topic of study (Benussi, 1913; Woodrow, 1928; Fraisse, 1946; Deutsch, 1986b), the number of studies is too small to enable us to construct a model that would predict how a time interval embedded in a series of time intervals is processed.

The problem of how complex temporal patterns are processed has mainly been explored through the study of rhythm perception (e.g., Essens, 1986; Povel, 1981; Summers, Hawkins, & Mayers, 1986). Ultimately, of course, the traditional time and rhythm perception studies should be related to each other in order to give a better understanding of temporal processing in music perception and production.

Although it is far beyond the purpose of our present study to integrate these fields, we can offer a modest contribution. We will discuss a new geometrical illusion of time perception that we discovered recently (Nakajima & ten Hoopen, 1988) and in the general discussion we will show that our findings can explain some of the published results in the field of rhythm perception.

The starting point of our research was an article by Israeli (1930), one of the first students who investigated context effects in time perception. He established effects of neighboring time intervals on the perceived duration of a standard time interval. We modified his paradigm in two ways: (1) we used tone bursts instead of light flashes to delimit time intervals and (2) we used much shorter intervals.
Our initial hypothesis concerning combining a standard time interval with a neighboring time interval was the assimilation hypothesis (e.g., Fraisse, 1978). That is, we expected the judged duration of the standard to change in the direction of the neighbor if the standard and the neighbor did not differ too much, irrespective of the order of the standard and the neighbor.

However, our pilot study showed a phenomenon that we could expect neither from Israeli’s data nor from the assimilation hypothesis. That is, the subjects’ judgments of the duration of the standard time interval were affected to a remarkable degree by a neighboring time interval, but only if the neighbor preceded the standard. In addition, this phenomenon could only be established when we used very short time intervals and when the preceding neighbor was shorter than the standard.

Experiment 1

This experiment was the first one in which the above-mentioned phenomenon found in our pilot experiment was systematically shown. We chose experimental conditions in which we would expect the effect of neighboring time intervals either to show up or not, according to our pilot study. Because this experiment was conducted in two different places, Leiden (The Netherlands) and Fukuoka (Japan), it was difficult to standardize the experimental conditions completely. For instance, the Leiden experiments were run on a Commodore Amiga 1000 computer whereas the Fukuoka experiments were done with a Teac PS-9000-216. We tried, however, to keep the conditions the same as far as possible. Moreover, one Dutch and one Japanese subject performed in both places at least in supplementary measurements.

METHOD

The stimulus patterns used for the control condition and the preceding-neighbor condition are depicted in Figure 1. All patterns consisted of empty time intervals marked by very short tone bursts. In the control condition, the standard time interval, S, was presented without any neighboring time intervals to create a perceptual context. In the preceding-neighbor condition, the second marker of the neighboring time interval, N, and the first marker of the standard time interval, S, were identical. In both conditions, a comparison time interval, C, started 5 sec after the beginning of S. The initial value of C could be either sufficiently long (descending series) or sufficiently short (ascending series) compared with S. The subject was required to adjust C to the same subjective duration as that of S. The physical duration of S, which will be also indicated by S afterward, varied among 120, 240, 480, and 720 msec for both the preceding-neighbor and the control condition. Two extra values of 60 and 960 msec were added in the control condition. The physical duration of N (indicated by N) for each S value varied along seven steps from \( \frac{13}{12} \times S \) to \( \frac{12}{11} \times S \).
Fig. 1. Time chart of the stimulus patterns. The very first presentation of the pattern in each trial was initiated by the computer. Afterward, the subject could trigger the pattern repeatedly by a mouse or switch command symbolized by the arrows. S = standard time interval, C = comparison time interval. N = neighboring time interval. All the time intervals were marked by very short sounds. The task of the subject was to adjust C to the same subjective duration as that of S, and he could present the pattern to himself as many times as he wanted.

After each presentation of a pattern, the subject, if he so desired, could lengthen or shorten C to various degrees by operating a mouse (Leiden) or a pair of switches (Fukuoka). There was no limit to the number of presentations within a trial. When satisfied with the match between C and S, the subject finished the trial, upon which the final physical duration of C was recorded as the point of subjective equality (PSE).

The time intervals were marked by 10-msec tone bursts of 1000 Hz whose waveform was approximately rectangular. They were presented via an amplifier [JVC AX-11 BK (Leiden) / AX-Z511 (Fukuoka)] monaurally through headphones (AKG K140). Their sound pressure level measured with an artificial ear (Brüel & Kjaer 4152) was about 80 dBA (Fast-Peak).

Four male subjects (three Japanese and one Dutch) with normal hearing participated, and four PSEs were obtained from each subject for each control and experimental condition.

RESULTS AND DISCUSSION

In the control condition, the averaged PSEs were almost equal to S, as shown in Table 1. Remarkable underestimations of S were caused by N when, and only when, S was 120 msec and N was physically shorter than S, as shown in Figure 2. The shortest N of 45 msec caused an underestimation whose relative amount was as great as 40%, which is obviously very large in this kind of experiment. Because such a stable and con-
TABLE 1
Mean Point of Subjective Equality (PSE) Values (N = 16) for the Standard Empty Time Interval (S) in the Control Condition of Experiment 1

<table>
<thead>
<tr>
<th>S(msec)</th>
<th>PSE(msec)</th>
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<tbody>
<tr>
<td>60</td>
<td>61.0 (10.1)</td>
</tr>
<tr>
<td>120</td>
<td>122.1 (10.3)</td>
</tr>
<tr>
<td>240</td>
<td>244.6 (20.1)</td>
</tr>
<tr>
<td>480</td>
<td>492.6 (35.4)</td>
</tr>
<tr>
<td>720</td>
<td>743.4 (47.0)</td>
</tr>
<tr>
<td>960</td>
<td>976.1 (61.0)</td>
</tr>
</tbody>
</table>

Note. Standard deviations in parentheses.

spurious underestimation appeared in a very simple context, we may call it a new illusion.

One may ask whether it is necessary that N and S be neighbors for this illusion to take place. If the illusion is caused just by the subject's comparison between N and S, it is possible that the same phenomenon appears even when N and S are separated by an interval of several seconds. This was not the case, however, according to our supplementary measurements (not reported here). Hence, it seems to be necessary for N and S to share the same marker for this illusion to occur.

Experiment 2

This experiment was conducted in Leiden in order to confirm the above-mentioned results by adding new subjects, gathering more PSEs and concentrating on relevant, that is, short S durations.

METHOD

This was almost the same as in Experiment 1. The value of S was 120 or 240 msec in the preceding-neighbor condition, and 60, 120, 240, or 480 msec in the control condition. A mouse was used for the subjects' adjustments. Stimulus patterns were presented diotically through the same headphones.

Five male subjects with normal hearing participated. Two of them (one Japanese and one Dutch) had already participated in Experiment 1 and the other three new subjects were Dutch. Eight PSEs were obtained from each subject for each stimulus condition.

RESULTS AND DISCUSSION

The averaged PSEs in the control condition were almost equal to S (see Table 2). The same illusion as in Experiment 1 appeared and is shown in Figure 3. Although there were some individual differences, the five subjects showed similar tendencies. One subject showed the same kind of
Fig. 2. Overestimations and underestimations of \( S \) caused by the preceding \( N \) in Experiment 1. The abscissa shows the physical duration of \( N \), and the ordinate “the PSE in the preceding-neighbor condition” minus “the PSE in the control condition,” that is, the overestimation. The shapes of the points indicate the individual subjects. The PSEs for each \( S \) in the control condition were averaged for each subject separately, and this value was used to calculate the overestimation in each trial in the preceding-neighbor condition. The vertical line above/below each point shows the standard deviation. An asterisk (*) at an \( N \) value means that the 16 independent comparisons between the preceding-neighbor condition and the control condition showed a significant difference (at the 5%/1% level) on a sign test. [Series (ascending or descending) and orders of measurements were considered for these comparisons. Comparisons showing equal values were omitted from the statistical treatment.]

illusion even when \( S \) was 240 msec. Both when \( S \) was 120 msec and when it was 240 msec, his averaged PSEs were nearly equal to the physical durations of \( N \) if \( N \) was physically shorter than \( S \). Another subject showed
TABLE 2
Mean Point of Subjective Equality (PSE) Values ($N = 40$) for the Standard Empty Time Interval (S) in the Control Condition of Experiment 2

<table>
<thead>
<tr>
<th>S (msec)</th>
<th>PSE (msec)</th>
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<tbody>
<tr>
<td>60</td>
<td>58.8 (12.1)</td>
</tr>
<tr>
<td>120</td>
<td>112.7 (21.7)</td>
</tr>
<tr>
<td>240</td>
<td>240.5 (21.4)</td>
</tr>
<tr>
<td>480</td>
<td>493.4 (35.4)</td>
</tr>
</tbody>
</table>

Note. Standard deviations in parentheses.

the same type of response when S was 120 msec. This may shed light on the mechanism of the illusion. These subjects may have perceived N and S as a regular temporal pattern, and the first time interval N may have worked as a framework to construct such a regularity.

Experiment 3

The natural question to be asked here is whether or not any overestimation or underestimation of the standard time interval, S, appears when a neighboring time interval, N, succeeds the standard time interval, S. Although our pilot study did not show a clear effect of a succeeding neighbor, we conducted two experiments, because they seemed necessary in order to elucidate the mechanism of the new illusion. Although Ex-

Fig. 3. Overestimations and underestimations caused by the preceding N in Experiment 2. (For details, see Figure 2 legend.) Forty independent comparisons between the preceding-neighbor condition and the control condition were used for the sign test for each N value.
Experiment 4 was conducted before Experiment 3, we reverse the order for the sake of clarity of exposition. Experiment 3 was conducted in Fukuoka.

METHOD

We used stimulus patterns for the control condition and the succeeding-neighbor condition as diagrammed in Figure 1. The control condition was the same as in Experiments 1 and 2. In the succeeding-neighbor condition, the second marker of the standard time interval, S, and the first marker of the neighboring time interval, N, were identical. In both conditions, a comparison time interval, C, started 5 sec after the beginning of S. The subject was required to adjust C to the same subjective duration as that of S. The physical durations of S and N were the same as in Experiment 1. Only the order in which they were presented was reversed. A pair of switches was used for the subjects' adjustments. The other details of the procedure were the same as in Experiment 1. Stimuli were presented monaurally through the same headphones. Six male Japanese subjects with normal hearing participated, and four PSEs were obtained from each subject for each stimulus condition.

RESULTS AND DISCUSSION

In the control condition, the averaged PSEs were almost equal to S, as can be seen in Table 3. Although some statistically significant deviations of the PSEs from S appeared, the amounts of these deviations were negligible for our purpose. Figure 4 shows no remarkable effect of the succeeding N on the duration perception of S. In order to obtain the same kind of illusion as in Experiments 1 and 2, it seems a prerequisite that N precedes S. In other words, the effect of context shows temporal asymmetry.

If we examine the data statistically, as indicated in Figure 4, however, some significant effects of N appear. When S was 120 or 240 msec, and the succeeding N was longer than S, S tended to be overestimated. This

<table>
<thead>
<tr>
<th>S(msec)</th>
<th>PSE(msec)</th>
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<tbody>
<tr>
<td>60</td>
<td>57.5° (4.4)</td>
</tr>
<tr>
<td>120</td>
<td>120.8 (13.7)</td>
</tr>
<tr>
<td>240</td>
<td>242.8 (13.2)</td>
</tr>
<tr>
<td>480</td>
<td>495.9° (19.5)</td>
</tr>
<tr>
<td>720</td>
<td>747.9** (29.1)</td>
</tr>
<tr>
<td>960</td>
<td>970.8 (50.2)</td>
</tr>
</tbody>
</table>

Note. Standard deviations in parentheses. An asterisk (*) indicates that there was a significant difference (at the 5%/1% level) between the PSE and S on a sign test. (There were no such differences in the other experiments.)
Fig. 4. Overestimations and underestimations caused by the succeeding N in Experiment 3. (For details, see Figure 2 legend.) Twenty-four independent comparisons between the succeeding-neighbor condition and the control condition were used in the sign test for each N value.

finding might be related to our illusion. That is, when two very short time intervals neighbor each other, and the first interval is physically shorter than the second interval, the first interval is overestimated while the second interval is underestimated. This could be a typical example of assimilation. When two similar objects are situated near each other, they can be perceived more similar than when separated.

In order to investigate the notion of assimilation further, we conducted a small supplementary experiment that used certain stimulus patterns of the preceding-neighbor condition of Experiments 1 and 2. The physical durations of the first/second time interval were 45/120, 95/120, 90/240,
and 190/240 msec. The markers were 5 msec instead of 10 msec. The task of the subject was to adjust the comparison time interval, C, to the same subjective duration as that of the "first" time interval (indicated as N in Experiments 1 and 2). The PSEs were compared with those in the control condition, where the standard time interval was 45, 95, 90, or 190 msec. Four values were obtained from each subject for each stimulus condition. Four male subjects participated (three Japanese, one Dutch).

A significant effect of the second time interval (according to a sign test as in Figures 2–4) appeared only when the first and the second interval were 45 and 120 msec, respectively. The first time interval of 45 msec was indeed overestimated. This shows the same tendency as in Experiment 3. It seems difficult, however, to apply the notion of assimilation here directly. That is, the second time interval (120 msec) was underestimated to a degree of about 50 msec in Experiments 1 and 2, whereas the first time interval (45 msec) was overestimated to a degree of only 5–16 msec by the four subjects in this supplementary experiment. The overestimations of the first time interval found in Experiment 3 and in this supplementary experiment were rather small compared with the outstanding underestimations of the second interval in Experiments 1 and 2.

Another overestimation of S in Experiment 3 was found when S was 240 msec, and N was physically shorter than S. There are some possible explanations for this phenomenon. A contrast, instead of an assimilation, between the longer S and the shorter N may have caused the overestimation of S. Another explanation is that the subjects may have judged the duration between the first and the third marker, instead of between the first and the second marker, because the second and the third marker were confused easily. Because this overestimation is not very remarkable, we would like to postpone this problem for our future research.

Experiment 4

This experiment was conducted in Leiden, directly after Experiment 2 and with the same subjects. The purpose was the same as in Experiment 3, that is, to study the effect of a succeeding neighbor. The advantage of this experiment is that we can compare the PSEs of Experiments 2 and 4.

METHOD

Instead of the preceding-neighbor condition, as in Experiment 2, the succeeding-neighbor condition (see Fig. 1) was used. The procedures of these two experiments were otherwise the same. Also the same subjects participated. The PSEs of the control condition of Experiment 2 were used also to analyze the results of this experiment. Stimulus patterns were presented diotically through the same headphones.
RESULTS AND DISCUSSION

The results shown in Figure 5 were very similar to those in Experiment 3. It is rather clear that S is overestimated when it is succeeded by a longer N. The overestimation of S also appeared when S is 240 msec and N is physically shorter than S. These tendencies appeared also in Experiment 3, although the amounts of these overestimations were small in both experiments.

We can compare the values in Experiments 2 and 4 by pairing the stimulus conditions that have the same physical durations (S and N). Figure 6 shows the results. The overestimations showed a systematic difference between the preceding- and the succeeding-neighbor condition. They were always greater in the succeeding-neighbor condition. That is, when two time intervals of certain physical durations neighbor each other, the preceding (or the first) position tends to give a longer subjective duration. This tendency appeared even when physically equal time intervals neighbored each other.

General Discussion

The most important finding was that, when two very short time intervals neighbor each other, and the first time interval is shorter than the second, the second time interval is underestimated to a remarkable degree. This phenomenon seems rather stable. An illusion in such a simple context should provide a good clue for the investigation of the perception of very short durations. Although the illusion appeared clearly only when the

![Graphs showing overestimations and underestimations caused by the succeeding N in Experiment 4.](image)

Fig. 5. Overestimations and underestimations caused by the succeeding N in Experiment 4. (For details, see Figure 2 legend.) Forty independent comparisons between the succeeding-neighbor condition and the control condition (from Experiment 2) were used in the sign test for each N value.
Fig. 6. Comparison between the preceding-neighbor condition and the succeeding-neighbor condition. The results of Experiment 2 (filled circles) and Experiment 4 (open circles) are shown together. Each point shows the mean overestimation value across the five subjects. An asterisk (*) at an N value means that the 40 independent comparisons between the preceding-neighbor condition and the succeeding-neighbor condition showed a significant difference (at the 5%/1% level) on a sign test.

The second time interval was 120 msec in the present experiments, an experiment that we did not report here showed the same phenomenon for various standard durations. When the standard is longer than about 200 msec, however, the illusion seems to disappear.

Some authors have suggested that the ratio between neighboring durations tended to be perceived closer to a simple integral ratio (Nakajima, 1979, 1987; Povel, 1981; Essens, 1986). The present illusion may be an example of this, because it should make the subjective ratio between the first and the second duration closer to 1:1. The ratio 1:1 is rather special because it can cause the perception of regularity (Schulze, 1978; Warren, 1982; Povel, 1984; Nakajima, 1987). It is also possible to introduce the notion of assimilation as we tried in the discussion of Experiment 3. This type of idea, however, cannot explain the illusion, because the illusion appears only when the standard is preceded by a shorter neighbor.

It may seem strange that the underestimation takes place only for the second time interval. However, it is quite usual that the perception of neighboring durations changes when their temporal order is reversed. Nakajima, Nishimura, and Teranishi's (1988) Experiment 1 provides an example. When two durations of 100 and 400 msec neighbored each other in this order, the subjective ratio between them was estimated as 0.339:0.661. When the temporal order of these durations is reversed, we would expect that the subjective ratio should also be reversed, namely
0.661:0.339. However, this was not the case. In fact, the estimated ratio between these durations was 0.720:0.280. Although the same physical durations were reversed, the subjective proportion given to the first time interval was greater (0.339 > 0.280 or 0.720 > 0.661). This tendency appeared when both of the neighboring durations were shorter than or equal to 600 msec. A similar tendency was found in Nakajima’s (1987) Experiment 2, where each temporal pattern consisted of three neighboring time intervals. When three physical durations of 50, 150, and 100 in that order were adjacent, the estimated ratio was 0.28:0.39:0.33. When the order of these physical durations was reversed, however, the estimated ratio was 0.37:0.38:0.25. Again, the first position was assigned a greater subjective proportion than the last position. Even when two physically equal durations were adjacent, the first duration was judged longer when we required the subjects to match each of these durations with another comparison duration in our present Experiments 2 and 4. (See the discussion of Experiment 4.) Thus, there are some examples of temporal asymmetries in the perception of very short neighboring time intervals, and our illusion gives another example. There is a common element in these asymmetries. That is, when the physical durations are equal, the preceding time intervals tend to be judged longer than the succeeding time intervals. We must keep this fact in mind when we consider the mechanism of our illusion.

The most interesting feature of our illusion is that it appears only when S is very short. This kind of restriction is rare in geometrical illusions of visual space, which are the most familiar illusions to perceptual psychologists. It has often been suggested that time intervals shorter than about 200 msec are qualitatively different in their perceptual nature from longer intervals. When short clicks are presented successively, with interonset intervals shorter than about 220 msec, it becomes difficult to count every click (ten Hoopen & Vos, 1981). When two short sound bursts are presented with an interonset interval shorter than about 150 msec, it becomes difficult to obtain a perceptual impression that can be associated with our bodily movements (Nakajima, Shimojo, & Sugita, 1980). These boundaries are not very far from the boundary where the present illusion appears or vanishes. This suggests that the listener can use his/her bodily movements or speech, at least implicitly, to “measure” time when the standard is longer than about 200 msec. It is possible that the illusion appears only when this timing mechanism does not work.

Although the mechanism of our illusion is not yet clear, we found some phenomena in the literature that may be caused by the same mechanism. Nakajima et al. (1988) reported a systematic discrepancy between the physical and the subjective ratio of two neighboring empty durations. The subjective ratio tended to be less extreme (nearer to 1:1) than was the
physical ratio. Suppose, for example, that two empty time intervals of 600 and 100 msec neighbor each other in this order (the physical ratio is 6:1). Expressing the ratio \( m:n \) as \( m / (m + n) \) for mathematical convenience, this ratio is expressed as 0.857. When the subjects estimated the corresponding subjective ratio, however, it was 0.78 on average, thus nearer to 0.5 (1:1). Nakajima et al. explained the discrepancy with the following psychophysical scale: \( \tau(t) = k(t + \alpha) \), where \( t \) denotes the physical duration, and \( \tau(t) \) is the corresponding subjective duration. The parameter \( k \) just indicates a proportional relationship, and \( \alpha \) is a constant of about 80 msec. Then, the subjective ratio in the above example should be \((600 + 80):(100 + 80)\), which is also expressed as 0.791. This predicted value is close to the empirical value shown earlier. This hypothesis, the “Supplement Hypothesis,” worked nicely in general to explain the discrepancy between the physical and the subjective ratio. In some cases, however, the empirical values deviated considerably from the prediction from this hypothesis. When two very short durations neighbored each other, and the first duration was physically shorter than the second, the estimated ratio tended to come even closer to 0.5 (1:1) than predicted from the hypothesis.

This deviation can be explained by our illusion. For example, when two empty time intervals of 50 and 100 msec neighbored each other in this order, their estimated ratio was 0.496, while the corresponding physical ratio is 0.333. Applying the Supplement Hypothesis, the subjective ratio should be about \((50 + 80):(100 + 80)\), expressed as 0.419, which is nearer to the obtained estimated ratio, but which is not close enough to support the hypothesis. If we consider that the second time interval was underestimated to some degree through the aforementioned illusion, we may be able to explain this deviation. Guessing the value of the underestimation roughly, it is about 30 msec in this example. Furthermore, the first time interval may be overestimated to the degree of 5 msec according to the supplementary experiment to Experiment 3. Then the ratio may be perceived as \((50 + 5 + 80):(100 - 30 + 80)\), expressed as 0.474. This value is not very far from the estimated ratio. We found a few more cases where we can apply this idea to Nakajima et al.’s data. A more systematic examination will be necessary in the future.

Schulze (1989) presented his subjects with isochronous tone sequences in which the last time interval was either correct or physically too long. Their task was to detect irregularity. Suppose that three tones marked two empty time intervals. Let \( t \) and \( t + \Delta t \) denote the physical durations of the first and the second time interval, respectively. Schulze measured the value of \( \Delta t \) that makes the irregularity just detectable, which we would like to call the irregularity detection threshold (IDT). If we could assume a relation similar to Weber’s law between the standard duration \( t \) and
IDT, the functional relationship between them should be proportional. Even when Weber’s law is modified as, for example, suggested by Getty (1975) or Nakajima (1987), the relationship should be at least increasing or constant at any point. This was not the case, however, in Schulze’s results. When \( t \) was 50 or 100 msec, the IDTs were greater than when \( t \) was 200 or 400 msec. That is, the subjects needed a greater difference between smaller physical durations in order to detect irregularity in the sequences. This fact is rather difficult to grasp intuitively.

Our illusion, however, can give a nice explanation. When two neighboring time intervals have physical durations of \( t \) and \( t + \Delta t \), where \( t + \Delta t > t \) as in Schulze’s experiments, the second time interval is underestimated, which reduces the effect of \( \Delta t \). Suppose that \( t = 50 \) msec and \( \Delta t = 20 \) msec. If the amount of underestimation of the second time interval is 10 msec, as a speculative example, then the second time interval may behave as if it had a physical duration of \( 50 + 20 - 10 = 60 \) msec. In other words, the effective amount of \( \Delta t \) is only 10 msec, which makes the irregularity less detectable. Therefore, the IDT should be longer. As the underestimation of the second time interval, according to our illusion, takes place only when it is shorter than about 200 msec, our analysis holds only for shorter durations. That is, the IDT is lengthened by our illusion only when the time intervals are shorter than about 200 msec. This explains the paradoxical phenomenon Schulze has described.

When he used more than four time intervals, the paradoxical phenomenon was no longer apparent in his data. If the above explanation of Schulze’s paradox is correct, this means that our illusion should disappear when we use more than three neighboring time intervals preceding the standard to be matched. Experiments are being performed to investigate this supposition.

It is an interesting attempt to relate our new illusion to phenomena found in a more musical context. Before making such attempts, however, it is necessary to explain the resemblance between our stimulus patterns and musical stimulus patterns. We used empty durations delimited by short sound markers with a rectangular amplitude envelope. Many instruments produce tones with a fast attack and a slow decay. The duration of a tone can be considered the time elapsing between its onset and the onset of the next tone. When the sound rises quickly, such a duration can be regarded as a pseudo-empty duration (Schütte, 1978; Sternberg, Knoll, & Zukofsky, 1982; Terhardt & Schütte, 1976; Nakajima, 1987). Therefore, if we are using phrases in the remainder of this discussion such as “underestimation or overestimation of musical notes,” we mean under-estimation or overestimation of the time elapsing between the onsets of two consecutive tones. Although this approach may be too rough to construct a precise psychophysical model of duration perception of musical
tones, it is a necessary first step to connect our experiments with musical behavior.

Drake, Botte, and Gérard (1989) reported a phenomenon in a context that seems related to our illusion. When several short musical notes, which had to be perceived in equal time values (musical durations), formed a series before a longer note, the last short note could be physically longer than the preceding notes. The listeners seem to have perceived equal durations even when this note was 5% longer in some conditions. This is a perceptual distortion in their terminology. When this note was shorter than the preceding notes, however, differences smaller than 2% were detected. If we consider that the duration of this note, when physically longer than the preceding notes, was underestimated because of our illusion, we can explain the matter in the same way as we explained Schulze’s (1989) paradox (Drake, personal communication, 1989). However, the present distortion was found when the physical durations of short notes were longer than 200 msec. Therefore, we must be careful in how we generalize this line of reasoning. There is also an important difference between the data of Schulze and the data of Drake et al. Schulze’s paradox appeared only when he used two or three very short time intervals. When he used five or six intervals, it almost disappeared. On the other hand, Drake et al.’s perceptual distortion appeared only when they used more than three short notes. At present, Schulze’s paradox seems closer to our illusion.

Gabrielsson (1974) showed that, when two short musical notes of the same time value neighbored each other, musicians tended to make the second note physically longer in performance. That is, the second note was often preceded by a note that was slightly shorter physically. The duration of the second note may be underestimated by the listener in some cases because of our illusion. Then, it is possible that the listener perceives equal durations despite the difference in the physical durations of these notes. This suggests that Drake et al.’s perceptual distortion can take place even when only two short notes form a series. The matter must be examined from the viewpoint of perceptual psychology.

Thus, we have obtained some previous data that may be susceptible to explanation by our illusion. The mechanism of the illusion itself, however, is not yet clear.¹

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