

Tactile duration compression by vibrotactile adaptation

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In the visual modality adaptation to high temporal frequency can result in spatially localized apparent duration compression. The principal point of adaptation is thought to be early in the visual system, at which point temporal information is encoded within sustained (parvocellular) and transient (magnocellular) channels. Here, we investigate whether the adaptation-based time compression could also be found in the tactile modality, which also has sustained (slowly adapting) and transient (rapidly adapting) neural channels. Our results showed that periods of vibration seem compressed when presented to a region of the skin surface adapted earlier to higher frequencies. This finding indicates that human duration perception can be altered by adaptation of temporal sensory channels in similar ways in vision and touch.

Introduction

Our sense of the passage of time operates over multiple scales from the microsecond precision of the inter-aural timing required for auditory spatial location to the hours of the circadian rhythm [1]. It is conceivable, but unlikely, that these various temporal systems rely on the same temporal mechanisms. Here, we investigate timing processing around the subsecond range, which is essential for event recognition and sensorimotor coordination.

In a visual timing study, it was reported that adaptation to a 20 Hz motion drift or flicker reduces the perceived duration of a subsecond 10-Hz interval when presented in the adapted region [2]. The following studies showed that the adaptation effect is highly space-specific [3], and that the adaptation effect occurs even for high frequency invisible flicker thought to stimulate subcortical but not cortical mechanisms [4]. The visual spatial specificity of apparent temporal compression clearly argues against a classical view that time is judged with reference to a central generic clock [5,6]. The overall properties of the time compression suggest that the principal point of the timing processing in the subsecond range is in the early visual system where temporal information is encoded through the sustained (parvocellular) and transient (magnocellular) channels, with selective adaptation of the latter channels causing the apparent time compression.

There are similarities in information encoding in visual and tactile modalities, specifically with respect to sustained (slowly adapting) and transient (rapidly adapting) neural response properties. In the four tactile response channels (mechanoreceptive afferents), the

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two slowly adapting channels (first channel associated with Merkel endings and the second channel associated with Ruffini-like endings) have low-pass temporal tuning characteristics to vibrating stimulation, and the other two rapidly adapting channels (first channel associated with Meissner endings and the second channel associated with Pacini endings) have band-pass temporal tuning characteristics [7,8]. Consequently, we investigated whether adaptation-based time compression could also be found in the tactile modality using flutter stimuli (vibration at frequencies approximately between 5 and 50 Hz). We measured the perceived duration of a 1-second flutter after adaptation to higher or lower flutter frequency.

As in the visual modality, we found compression of perceived time for flutter vibration presented to a region of the skin surface adapted earlier to higher temporal frequencies. This finding suggests that the two sensory modalities have similar sensory mechanisms for sub-second duration encoding.

A part of this study was reported in the annual meeting of the Society for Neuroscience, 2007 [9].

Materials and methods

Participants

Seven right-handed participants [five naive and two of the authors (T.A. and S.N.)], aged 24–47 years, participated in most of the experiments reported below (for some control experiments participants were selected from this pool). They had no known abnormalities of their tactile sensory systems. Informed consent was obtained from the naive participants before the experiment started. Recruitment of the participants and experimental

procedures were approved by the NTT Communication Science Laboratories Research Ethics Committee, and were conducted in accordance with the Declaration of Helsinki.

Apparatus

We measured perceived duration after adaptation to vibration at the same finger location. We also measured perceived flutter frequency after adaptation to see whether vibration frequency was altered by the adaptation as found in vision. This is not only an interesting question in its own right, but also highly relevant to duration perception, as apparent duration change could be a secondary effect of apparent flutter frequency change [2]. Finger pads of the right and left index fingers were stimulated by small pins (6.0 mm in diameter) (Fig. 1a). Sine-waveform vibrations (maximum amplitude 0.6 mm) were delivered to each pin by a vibration generator (511-A EMIC Inc., Kyoto, Japan). A circular plastic plate was placed at the top of the vibration generator. The participant placed the index finger on a hole (7.8 mm in diameter) at the center of the plate, and touched the pin through the hole. Unless otherwise noted, the tip of the pin (at the highest position) was 0.72 mm below the top surface of the plate. As a result, the pin stimulated the participant's skin only when activated. The sound of the vibrator was masked by a recording of vibrator noise, presented using Apple in-ear headphones (Apple, California, USA) covered with Peltor Optime II Ear Defenders (3M, Minnesota, USA) or Sennheiser HD202 headphones (Sennheiser, Hannover, Germany). A translucent plastic cover visually obscured the hands and stimulator to the participant (Fig. 1b).

Procedure

In the adaptation phase, a 35, 25, or 15 Hz-vibration was presented to one finger for 60 s at the beginning of an experimental block, and for 20 s before each test trial. We also included a 0 Hz condition in which participants adapted to the touch of a static pin. In the duration experiment participants reported the relative duration of a 25 Hz 1000 ms standard presented at the adapted location against a 25 Hz comparison presented to the unadapted finger whose duration varied between 700 and 1400 ms (700, 800, 850, 950, 1000, 1050, 1150, 1250, 1400 ms). In the frequency experiment participants reported the relative temporal frequency of a 25 Hz 1000 ms standard presented at the adapted location and a 1000 ms comparison presented to the unadapted finger, whose temporal frequency was varied between 12.5 and 50 Hz (12.5, 18, 20, 23, 25, 27, 30, 33, 50 Hz). The order of the standard and comparison was randomized from trial to trial to avoid order effects. In each case we derived psychometric functions based on 24 trials per data point. The point of subjective equality, derived from the 50% point on the cumulative Gaussian fitted to the psychometric function, provided an estimate of the

perceived duration or temporal frequency depending on the task.

In a control experiment we asked participants to judge the temporal order of the onset or offset of an interval of tactile stimulation relative to the time of occurrence of the onset or offset of an auditory tone (1000 Hz). The resulting psychometric functions were fitted by a cumulative Gaussian and the 50% point on the function provided an estimate of the apparent time of occurrence. We calculated the onset/offset time differences between adaptation and no adaptation conditions. In another control experiment we manipulated signal strength by varying the percentage of time for which the vibrator was switched on within a unit cycle time (e.g. 40 ms for 25 Hz). For example, if the ratio of time for contact (duty cycle) is 25% for 1000 ms 25 Hz, the vibration contains 25 blocks of 40 ms unit time including 10 ms for contact. Participants reported the relative duration of a 1000 ms auditory tone (1000 Hz) as compared with a 25 Hz test vibration with one of the three contact ratios (25, 50, and 75%), whose duration varied between 700 and 1400 ms. The point of subjective equality provided an estimate of the relative perceived duration of each contact ratio against a tone of 1000 ms.

Results

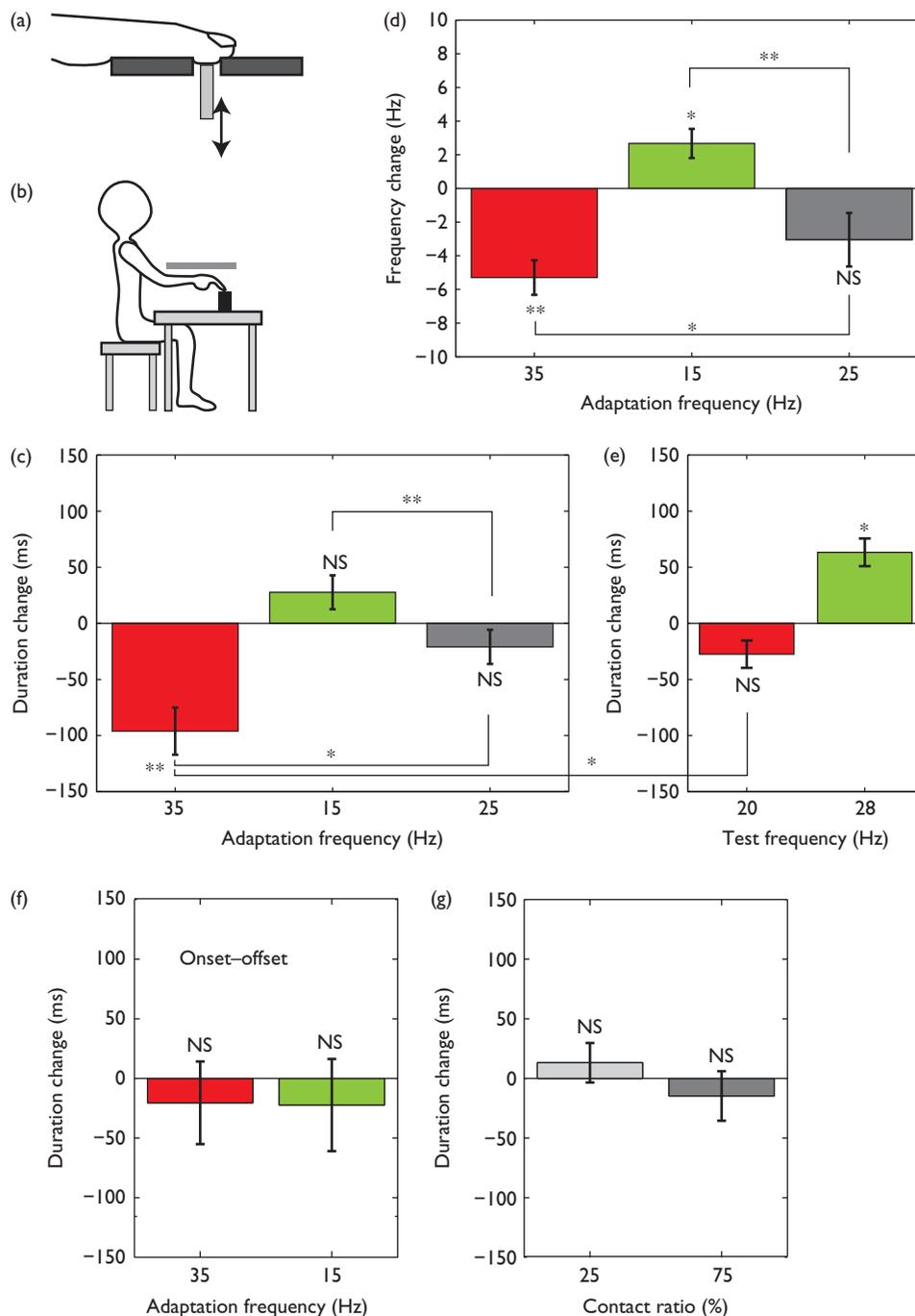
Duration and frequency judgments

Figure 1c shows adaptation effects on duration judgments. After adaptation to a period of 35 Hz flutter, the apparent duration of a 25 Hz flutter was reduced from 1000 ms to approximately 900 ms (a 10% reduction) [$t(6) = 4.57$, $P = 0.004$, paired t -test]. As in the visual modality, adaptation to a higher temporal frequency can produce a subsequent apparent compression of duration. After adaptation to 15 Hz the perceived duration slightly increased, but this effect did not reach statistical significance [$t(6) = 1.83$, $P = 0.117$]. In addition, no temporal compression was observed when participants adapted to the 25 Hz flutter [$t(6) = 1.38$, $P = 0.217$] or to the 0 Hz flutter [$t(3) = 0.22$, $P = 0.84$], indicating that adaptation to vibration rather than just finger pressure is essential for the changes in tactile duration perception.

Figure 1d shows adaptation effects on frequency judgments. After adapting to 35 Hz the apparent frequency of the 25 Hz test vibration was reduced to approximately 20 Hz [$t(6) = 5.00$, $P = 0.002$], whereas after adaptation to 15 Hz it increased to approximately 28 Hz [$t(6) = 3.09$, $P = 0.022$]. The apparent frequency was slightly reduced after adaptation to the same frequency, but this effect was not statistically significant [$t(6) = 1.62$, $P = 0.157$].

To determine whether the duration effect was mediated by the change in apparent temporal frequency, we directly compared the apparent duration of a 20 Hz and 28 Hz flutter against a 25 Hz standard stimulus. As shown in Fig. 1e, the perceived duration of the 20 Hz flutter was

Fig. 1



(a) Illustration of a finger stimulated by a vibrating pin. (b) Illustration of bodily posture of a participant and arrangement of apparatus. (c) Apparent duration change after adaptation to a 35, 15, and 25 Hz. (d) Apparent frequency change after adaptation to a 35, 15, and 25 Hz. (e) Apparent duration change of a 20 Hz and 28 Hz vibration relative to that of a 25 Hz vibration. (f) Sum of the onset and offset errors. (g) Apparent duration change of vibration with 25 and 75% contact ratios relative to that with 50% contact ratio (standard stimulus). * P value less than 0.05 and ** P value less than 0.01. NS, not significant.

approximately 25 ms less than the standard [$t(6) = 2.26$, $P = 0.065$]. The duration of 28 Hz flutter seemed to last for approximately 50 ms longer than the standard [$t(6) = 5.14$, $P = 0.002$]. Thus, there was an effect of flutter rate on perceived duration in the direction consistent with the

adaptation effects. However, the magnitude of rate-induced time compression was not strong enough to account for the adaptation-induced time compression, as the duration compression obtained under the 35 Hz adaptation condition was significantly larger (by approximately

75 ms) than that obtained under the 20 Hz flutter conditions [$t(6) = 2.82$, $P = 0.031$], while the duration expansion obtained under the 15 Hz adaptation condition was not significantly different from that obtained under the 28 Hz flutter conditions [$t(6) = 1.33$, $P = 0.232$]. In addition, for selected participants, we measured the apparent duration change after 35 Hz adaptation with matching apparent frequency between the standard stimulus (25 Hz) and comparison stimulus (perceptually equivalent frequency of postadaptation 25 Hz, 21 Hz for these participants), and obtained a compression effect (27.2 ms for T.A., and 77.0 ms for S.N., whose compression effect with the original 25 Hz comparison was 56.3 ms and 120.3 ms, respectively). These results indicate that the change in apparent temporal frequency cannot account for the apparent duration compression after 35 Hz adaptation, and this parallels the pattern of data found in the visual modality. (This conclusion is further supported by a recent conference report [10] that adaptation-induced tactile time compression remained even after compensation for the changes in apparent velocity.)

Control experiments

In vision changes in apparent duration can occur without any change in the apparent onset or offset of the stimulus [2], indicating that the effect of adaptation does not simply alter the neural onset or offset latencies of a stimulus. To measure whether adaptation alters the apparent onset or offset of the tactile test stimulus participants judged the onset or offset of the stimulus against the onset or offset of an auditory tone. We found that the sum of the onset and offset errors did not differ from zero [$t(3) = 0.58$, $P = 0.60$ for 35 Hz; $t(3) = 0.59$, $P = 0.60$ for 15 Hz] (Fig. 1f).

It is known that adaptation reduces the strength of the tactile signal at test [11] and this reduction in strength may mediate the change in apparent duration. To check this we compared the apparent duration of the 25 Hz vibration signal produced by various ratios of contact time between the skin and pin (25, 50, and 75% of the unit cycle time). Although the vibration stimuli felt weaker or stronger, there was no change in perceived duration [$t(3) = 0.80$, $P = 0.49$ for 25% vs. 50%; $t(3) = 0.71$, $P = 0.53$ for 75% vs. 50%] (Fig. 1g). (As our system was not designed to flexibly change the vibration magnitude, we changed duty cycle to control apparent vibration strength. It should be added, however, that when we manually reduced the vibration magnitude by lowering the height of the pin relative to the plate surface, we found no time compression again.)

Discussion

In our experiments, we used a 25 Hz test that will stimulate all tactile channels to some degree [12]. The test frequency used in the visual studies was 10 Hz [2],

which is close to the peak sensitivity of the visual system and which generates similar activation in sustained (parvocellular) and transient (magnocellular) channels [13,14]. It has been suggested that high temporal frequencies stimulate the more adaptable magnocellular neurons [15], and modulation in transient channels is the prime determinant of distortions of subjective time in vision [2,16,17]. The misperceptions of tactile duration might also be ascribed to distortions in the transient-channel-based temporal coding system.

Although the main focus of this study is a shift in perceived duration in the tactile modality, as far as we are aware a shift in perceived frequency after adaptation to higher and lower frequency flutter has not been reported before. This provides another line of evidence for the similarity in sensory temporal coding across different modalities.

Given the dissociation of the effects of adaptation on perceived duration and perceived frequency, these effects are likely to have different neural substrates. Neural mechanisms underlying flutter frequency discrimination around our test frequency have been extensively investigated [18,19]. Although, adaptation to vibrotactile stimulation has been found at the receptor level [20], at the level of cuneate nucleus [21] and in the thalamus and in the cortex [22,23], it has been shown that there is significant covariation between psychophysical responses and evoked firing rates in primary somatosensory cortex (S1) [24], therefore, it is reasonable to expect that the effects of adaptation on apparent flutter frequency may reflect the firing rates of cortical neurons in S1. At present, we have little knowledge about neural mechanisms whose adaptation would lead to changes in perceived duration. How they are related to the mechanisms for flutter encoding, and to those for time processing in other modalities remains an intriguing open question.

Conclusion

We have showed for the first time that an adaptation-based time compression occurs in the tactile domain indicating that humans have adaptable sensory components of duration perception in another modality as well as vision. Our results also provide evidence for distributed (rather than centralized) components of time perception in multiple sensory systems.

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