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Amplitude and Duration Interdependence in the Perceived Intensity of Complex Tactile Signals

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Abstract. The dependency of the perceived intensity of a short stimulus on its duration is well established in vision and audition. No such phenomenon has been reported for the tactile modality. In this study naive observers were presented with pink noise vibrations enveloped in a Gabor wavelet. Characteristic durations ranging between 100 and 700 ms and intensities ranging from 0.3 and 3.0 10^{-3} m/s^2 were presented to the fingertip. Using a two alternative forced choice staircase procedure, the points of subjective equivalence were estimated for the 400 ms long reference stimulus. Similarly to vision and audition, lower intensities were consistently reported for shorter stimuli. The observed relationship could be interpreted as reflecting a mechanism of haptic constancy with respect to exploration speed.

Keywords: Psychophysics, Perception, Intensity, Tactile, Haptics, Gabor envelope

1 Introduction

For many sensory modalities, the perceived intensity of a stimulus tends to depend on the time of exposure to the stimulus. In audition, the perceived intensity, termed loudness, grows approximately as a power function of the duration of a stimulus shorter than 150 msec [8, 13]. Similarly, the sensation of pain evoked by electrical stimulation of teeth [12] is more intense if the stimulation is presented for a longer time. In vision, a positive and approximate power law relationship is also seen between the perceived brightness of a light source and the exposure time [2, 4]. This law holds for different aspects of our visual perception [7] suggesting that it reflects the overall response dynamics of the photoreceptors responsible for vision. These findings question whether the approximately proportional relationship between the duration of the stimuli and its perceived intensity could represent a general law of perception, a property that was dear to the Gestalt psychologists, like the laws of motion perception or the laws of perceptual grouping. Such a relationship can be expected to be found in the tactile modality.

A few studies investigate tactile intensity perception, but the literature is dominated by studies regarding detection thresholds and, on the other hand of the scale, by the effect of strong, unpleasant and potentially noxious vibrations,

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e.g. [6]. Verrillo showed that for a vibrotactile signal below 350 Hz, the frequency obeys a Steven's power law function with respect to the perceived intensity [14]. To the best of our knowledge, there has been no work on the dependency of perceived intensity of a tactile stimulus on its duration. Human tactile frequency discrimination being so limited [5], duration has the potential to yield a more pertinent relationship.

Because the somatosensory system has longer integration time constants than the auditory system, transients presented to the skin must last 5 to 10 times longer than those presented to the ear to obtain comparable effects [3]. On the other hand, von Békésy also found that the growth of sensation intensity on the finger tip is much like the growth of loudness in hearing. Therefore, a power law relationship should also hold for the tactile modality. We expect, however, the relation to be less steep than for audition since the auditory system is considerably more sensitive at amplitude discrimination for a given time than the somatosensory system.

We report here the results of a study on equal perceived intensity tests using a two alternative, forced choice staircase procedure. Ten observers were asked to compare the intensity of two consequently presented pink noise Gabor wavelets, varied in amplitude and duration. Pink noise was used to keep consistent with studies in other sensory modalities [1, 9]. It reduced the discomfort experienced with monochromatic stimuli [11], since 'ecological' tactile stimuli are naturally broadband and tend to conserve the same signal energy per frequency band [17]. Additionally, pink noise has no strict spectral localisation and thus can be assumed to be stimulating all the somatosensory sub-modalities.

2 Methods

Apparatus. The setup comprised of a generic laptop computer with an audio channel linked to an audio amplifier which drove a motor (Haptuator, Tactile Labs, Saint-Bruno, Quebec, Canada). The motor was bonded to a 3 mm aluminium plate, under which four hard rubber cylinders were placed perpendicularly to the vibrotactile transducer to allow free vibration-induced movements (see Fig. 1a). Thus, the plate could vibrate freely, impeded only by minimal rolling friction. The lightness of the plate and the strength of the motor allowed for a vivid sensation of vibration when the finger was placed on the plate.

Stimuli. Pink noise signal was generated in Matlab (R2011a, Mathworks) at a 44100 Hz sampling frequency. It was generated by applying an inverse Fourier transformation to amplitude coefficients proportional to the frequency and to random phase coefficients. In order to fit the bandwidth of the amplifier to that of the motor, the signal was subsequently filtered using a high-pass Butterworth filter with a 70 Hz cut-off frequency. The filter served to compensate for the natural frequency of the transducer, flattening the response in the low frequencies.

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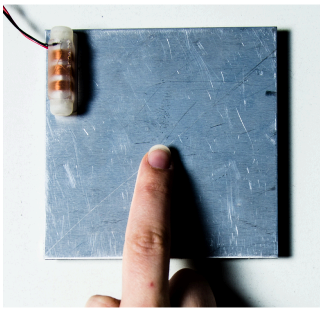
The stimulus,

$$\psi_{\delta t}(t) = A \exp\left(\frac{-\pi\,(t-t_0)^2}{2\delta t^2}\right) I(t), \tag{1}$$

was the product of a Gabor envelope of characteristic time, δt, with a pink noise signal, $I(t)$ of amplitude, A. The system was calibrated using an accelerometer bonded onto the plate and oriented in the direction of the vibrotactile motion. Test were made in the presence of the finger for several stimuli with different durations and amplitudes.



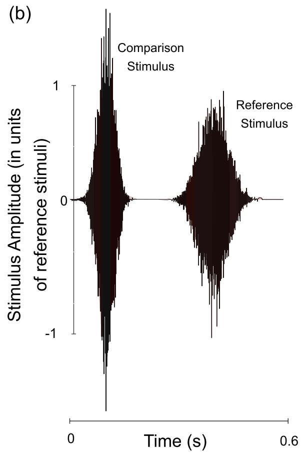


Fig. 1. (a) Apparatus. The right index was placed on an aluminium plate supported by four rubber cylinders, controlled by a vibrotactile transducer. (b) Example of the signal in one test : two consecutive pink noise Gabor enveloppes.

Observers. Ten right-handed volunteers (two female and eight male), 22 to 36 years old, with no history of neurological disorders or manual sensorimotor function disorders, participated in the study. The observers were naive to the aims of the study. They all gave their informed consent for the experimental procedure, in line with the Ile de France ethics committee.

Protocol. The observers sat in a chair, wore noise-cancelling headphones and a blindfold. They put their hands on the table, with the right elbow on the table top, and gently placed the right index finger on the plate. The left hand was on the computer keyboard.

They were presented with a sequence of two stimuli, one of them being the reference and the other one being a comparison. The order of the stimuli was random; the interstimulus pause was also random ranging between 300 and 800 ms. They were asked to report which of the two consequent stimuli felt stronger

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by pressing one of two keyboard keys denoting the first and the second stimulus respectively. The reference signal had an amplitude $A = 1.5\ 10^{-3}$ m/s^2 and a duration $\delta t = 400$ ms. The comparison stimuli had amplitudes ranging between 0.3 and 3.0 10^{-3} m/s^2 and δt could be 100, 200, 300, 500, 600 or 700 ms. Examples of stimuli are presented in Fig. 1b.

The experiment was organised into six sub-sessions corresponding to different durations δt of the comparison stimuli. The order of sub-sessions was balanced among observers. Within each sub-session the amplitude of the comparison stimulus was selected using two interleaving staircases, one starting at 2.0 of the reference amplitude and the other starting at 0.2 of the reference amplitude. The order in which the two staircases were presented was always random. The staircase step size was fixed at 0.2. Each trial started with the stimulus presentation and ended with the observer pressing the key reporting the subjectively stronger stimulus. The duration of each trial never exceeded 5 seconds; the overall experiment took about 20 minutes.

Data analysis. The responses of each observer for two staircases were pooled together and a single psychometric curve was determined by fitting it with the cumulative normal distribution function. The point of subjective equivalence, μ, between the reference and comparison stimuli is the amplitude at which the psychometric curve crosses a probability of 0.5. Psychometric curves were discarded if left boundary values exceeded 0.1 or if right boundary values were smaller than 0.9. The μ values determined from the retained curves were then used for further analysis. The regression coefficient between stimulus duration and the perceived equivalence amplitude was computed. It was justified using non-parametric Durbin test ('durbin.test' function, 'agricolae' package, R statistical software) with observers as judges and the duration δt as treatment. In order to have a balanced experimental design, the data of the observers who had at least one discarded psychometric curve were excluded from the statistical analysis.

3 Results

For each observer two staircases, one rising and the other descending, usually converged to values close to the bias, justifying the pooling of their data (see example in Fig. 2a). The observers' responses could usually be fitted rather well with a psychometric curve (see example in Fig. 2b). In some cases, however, the slope of the curve was too shallow, suggesting a low quality estimate of the point of subjective equivalence. Overall, five psychometric curves in four observers, which corresponds to less than 10%, have been discarded on this basis. The discarded curves mostly corresponded to the shortest stimulus duration (100 ms; three curves). The staircases for higher δt values usually had points of subjective equivalence closer to zero (see Fig. 2c), suggesting an inverse relationship between the stimulus exposure time and its perceived intensity. This trend, visible from the average data in Fig. 3, was also confirmed by the Durbin test: the effect of the duration on perceived intensity is highly significant ($p < .001$).

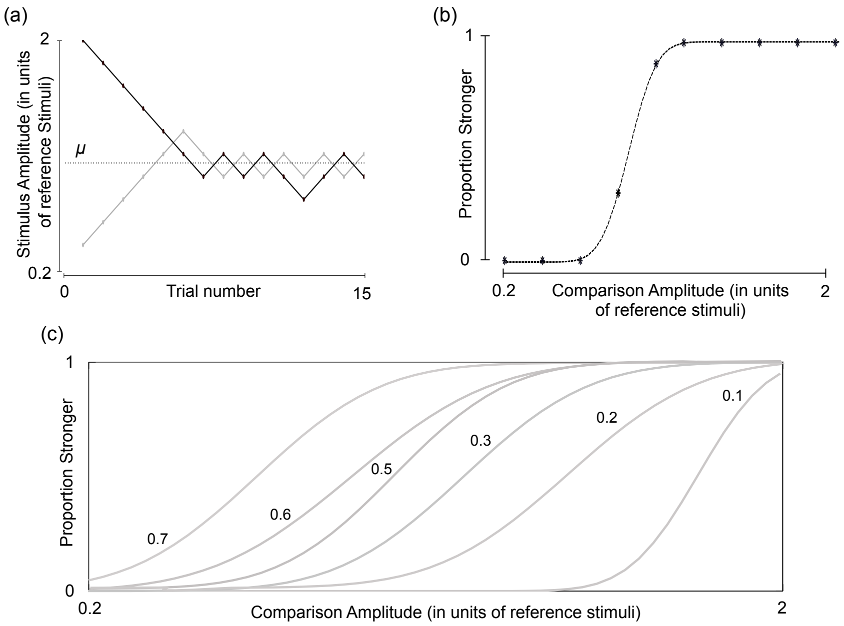

Fig. 2. (a) Staircase for one participants at δt = 0.5 s. The test converges to the amplitude at which the two signals feel identical, called the point of subjective equivalence. Here, $\mu \approx 1.1$. (b) Psychometric curve fitted to the points for the same test. μ is found at proportion stronger = 0.5. (c) General trend of the psychometric curves with time: psychometric curves for δt = 0.7, 0.6, 0.5, 0.3, 0.2 and 0.1 s.

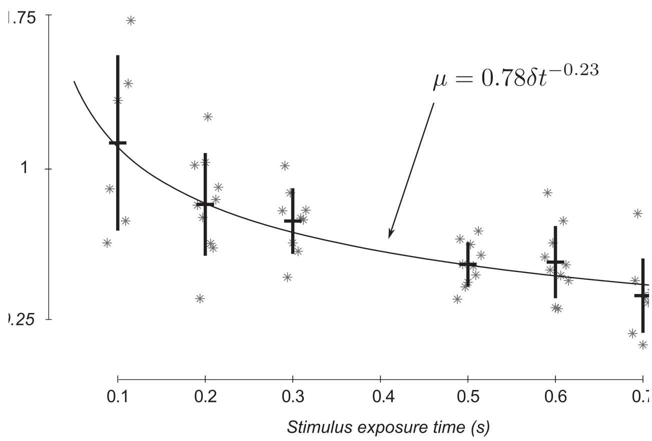

Fig. 3. The amplitude of subjective equivalence μ as a function of the stimulus exposure time δt, showing a negative power law relationship with a regression coefficient of -0.23.

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4 Discussion

The current study explored the relationship between the duration of a tactile stimulus and its perceived intensity. Such a relationship is well known in audition [8, 13], vision [2, 4] and pain [12] perception, but, to the best of our knowledge, has never been reported for the tactile modality. Our results show that in the case of a windowed vibratory skin stimulation, the perceived intensity is negatively correlated with the temporal dimension of the window. In this sense, the tactile modality is similar to the other modalities, and this negative correlation might be viewed as a non modal-specific law of perception.

The temporal dependency could be related to the biotribology of the skin. Indeed, the characteristic time of the skin deformation could prevent the vibrations from propagating within the given time window. We could for example think that at short times, it is the lack of skin response, not the stimulus duration perception, that creates the necessity for an increase in amplitude. However, the characteristic time of the skin and of the bulk fingerpad skin is just of the order of a few milliseconds [15, 10, 16] and thus would unlikely cause any noticeable difference in perception.

One could surmise the existence of a mechanism to ensure the constancy of tactile perception when a finger swipes over an asperity. One perceives an asperity by and large in the same way independently of the velocity at which one explores it. This could be explained by an adustement mechanism in the brain. When one swipes an asperity more rapidly, the skin oscillations are stronger and hence yield a more intense sensory stimulus. However, the intensity of the received sensations are felt less strongly to match the expected spatial dimension of the asperity, and hence the temporal window of the vibrations it creates. With such a mechanism, a temporally longer stimuli would need to have a lower amplitude than a temporally shorter simuli for the same spatially asperity to be felt with the same coarseness.

The pink noise stimuli used here can be seen as the input of a finger sliding over an uneven surface. In this case, the duration of the stimuli corresponds to the spatial extent of the asperity or to the velocity of the finger motion. The inverse relationship between the intensity of the perceived stimulus and its temporal duration, may thus correspond to the same constancy. This suggests that, unlike the auditory system, the tactile system might not be tuned to the discrimination of duration.

Since the majority of the skin receptors are sensitive to both the skin deformation and its temporal derivative, it can be assumed that the same asperity explored at a different speed creates the same deformation, but at different velocity. Thus, for the same surface asperity, instantaneous output of the skin receptors will be stronger if the exploration speed is higher.

Pink noise being a broadband signal, all the submodalities of mechanoreceptors (slowly and rapidly adapting) are likely to be excited. For the tactile modality, it takes time for the sensation magnitude to develop to its full power, about one second according to von Békésy [3]. In our study, the signals (0.1 to 0.7 s) and the interstimulus pause (0.4 s) do not allow the stimulus to fully

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develop into a conscious percept. However, we did not observe a steepening of the regression at smaller stimuli times, where we would have expected an overcompensation. This could suggest that the rapidly adapting afferents are predominantly recruted instead of the slowly adapting ones. It could also imply that the slowly adapting afferents are also recruted but that the coding of the incoming stimulus is much faster than previously reported and that it is the decay of the signal which takes time.

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