A Case of Perceptual Completion in Spatio-Temporal Tactile Space

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Abstract. We reproduced a perceptual phenomenon where a tactile stimulus moving on the fingertip jumps instantly over a gap but is felt as if the space of the gap was perceptually obliterated. This phenomenon was recently demonstrated on the forearm using brushes. On the fingertip, we elicited this effect using virtual edges and measured psychometric response curves obtained by varying the time taken by the moving edge to traverse the gap between the first and the third portion of the stimulus. Most people failed to detect 2 mm gaps when the traversal time fell below 0.2 s. The gaps were consistently detected when they were traversed at same the speed as that of the moving edge in the first and third portion of the stimulus. We discuss the implications of these findings.

Keywords: tactile perceptual completion, spatiotemporal stimuli

1 Introduction

Perceptual completion is when a percept includes features that are not represented in the raw sensory input or when observers fail to detect missing portions of the raw sensory input that our perceptual system restores in order to establish some form of assumed phenomenal regularity [6, 21]. Different forms of perceptual completion can then be discussed in terms of the different types of regularities that are locally violated and globally reinstated. Perceptual completion phenomena can be observed at all levels of processing by perceptual systems, from early detection to cognition. This singularly important family of phenomena can therefore take many forms and was reported in vision, audition, and touch.

In vision, well-known instances of completion are the so-called 'subjective contours' that appear when there is a "jump" in the stimulation created by partially occulting a geometrical figure by another [17]. Other examples are related to the retinal blind spots that go noticed by patients affected by scotoma in the same manner by which the natural retinal blind spots go unnoticed under most circumstances. Interestingly, the completion of artificially induced blind spots often, but not always, requires the presence of some kind of motion in the visual input induced by twinkling or counter phase gratings [27].

In audition, silent gaps that are inserted in an auditory stream of discrete tones with different frequencies are as important as the tones themselves and thus are not treated as interruptions [7]. A family of phenomena termed 'auditory induction' are observed when listening to certain auditory patterns with temporal continuity. Illusory sounds can be heard during short periods of silence or can be heard at illusory intensity levels [31]. These auditory phenomena can also be related to the restoration by our perceptual system of forms of continuity that are specific to auditory scenes [19]. A similar phenomenon can be observed when vibrations are felt rather than being heard, which suggest the existence of common mechanisms in audition and touch for processing temporal streams [20].

In touch, an important source of stimulation is when objects slide (or roll) on the skin [14]. It is an essential source of stimulation which may, or may not, be associated with the displacement of a locus of stimulation on the skin. When an observer produces no motor output, however, provided a proper set of prior assumptions [13], the displacement of a locus of stimulation may be associated to the movement of an object relatively to the body region being stimulated. Objects, however, do not move in arbitrary manners. The laws that governs the motion of objects require that certain quantities must be conserved with the consequence that all displacements must be continuous, even during collisions between hard objects, which, together with damage — as in the snapping of an elastic band — are the "most discontinuous" forms of mechanical behaviour. In other words, objects do not jump instantaneously, even during the most abrupt interactions.

A recent study by Seizova-Cajic and Taylor, in what could be one of the most compelling case of perceptual completion in the tactile domain, reported that gaps of 10 cm in size inserted in stimuli sliding on the skin of the forearm were unnoticed, as if space was abridged, if the traversal duration was nulled artificially [28]. Two brushes 10 cm appart were concurrently displaced at the same speed. To practically realise zero-duration gaps, an occluding plate was positioned on the forearm such that only one of the two brushes would come into contact with the skin at any given moment in time. This clever apparatus nevertheless put constraints on the testing method that could be employed and the authors resorted to a magnitude estimation protocol.

The purpose of the present study was to investigate this phenomenon on the fingertip rather than on the forearm. To this end, we took advantage of a tactile display device capable of eliciting salient moving stimuli on the fingertip. The availability of a computer-controlled stimulus generation apparatus made it possible to measure psychometric response curves. The present pilot study revealed that 2.0 mm gaps in a stimulus moving on the fingertip skin at a speed of 2.0 mm/s would become undetectable for jump durations smaller than 0.2 s. The positive results of present study thus motivate us to pursue further investigation of this perceptual completion phenomenon, with the aim of clarifying the conditions in which it takes place, to propose perceptual models applicable to moving tactile stimuli, and to investigate possible mechanisms.

Figure 1 schematically represents the stimuli that we employed, the manner in which they varied, and the phenomenology they elicited. The stimulus was composed of three phases. An edge-like virtual object first moved on the skin for a certain distance, here at the fingertip, disappeared, and reappeared in a third phase beyond a gap separation. In one limit condition, depicted by Fig. 1a, the time elapsed until the re-appearance

corresponded to that of an object moving at constant speed throughout the whole stimulus. In this limit case, the sensation was by and large veridical. In the other limit condition, depicted by Fig. 1c, the edge-like virtual object proceeded to the third phase with an instantaneous 'jump', as in Seizova-Cajic and Taylor's experiment. When the delay duration was zero, the presence of a gap became undetectable by most people. Testing conditions were cases in between these two limit conditions, and the participants were asked to report the occurrence of a jump, or discontinuity in their sensation.
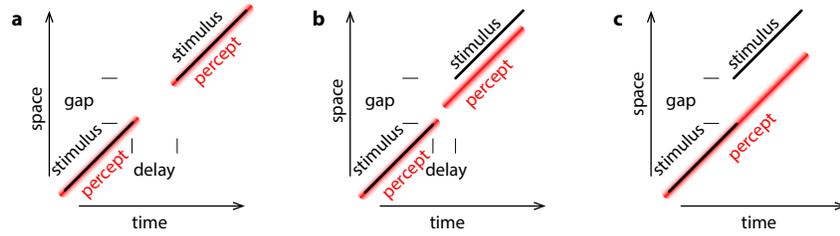

Fig. 1. Phenomenology. **a**, a virtual edge moves on the skin and disappears over a gap for a duration compatible with constant speed. **b**, The virtual edge moves 'too fast' in the gap. Equivalently, delay for reappearance is reduced. The gap is felt to be smaller. **c**, The virtual edge moves at "infinite" speed over the gap. Equivalently, delay is zero. The gap is not detected.

2   Method

2.1   Apparatus

The stimuli were generated by the 'Latero' (Tactile Lab, Montréal, Canada), a commercially available version of the device described in [30]. This device operates by applying a traction distribution on the skin. The 10×10 mm display surface was subdivided in 64 contact surfaces with a spatial period of 1.2 mm. Each of these contact surfaces was individually commanded to move laterally. The device, represented in Fig. 2a, was encased in a protective shell such that the display surface was flush with the upper shell surface on which a fingertip could be placed.

It is important to realise that, while the display surface was composed of discretised tiles, the spatiotemporal stimuli generated by this device did not rely on an apparent motion phenomenon to generate sensations varying in time and in space, but are physically smooth and continuous, even when they move slowly. This property is owed to a case of "natural" computation performed by the laws of contact mechanics that play the role of a reconstruction filter in the spatial domain.

Briefly, at a depth commensurate with the spacing between two opposing tractions, the subcutaneous strain field created by local differential traction has the character of a Gaussian function for its normal component and of the derivative of a Gaussian for its shear component [29, 26]. This effect is schematically represented in Fig. 2b. When patterns of deflection are combined by linear superposition, this property is preserved,

as shown by Fig. 2c. In other words, two superposed adjacent virtual edges have the character of a wider edge without any other form of processing than the effects of contact mechanics in the skin [15]. An important consequence is that moving patterns are smoothly interpolated in space. A moving edge is created by reducing the distance between a pair of traction surfaces, concurrently increasing it in the next pair. The edges generated by the display device can be made highly salient if they are rapidly modulated in time. Incidentally, strong and rapid fluctuations due to frictional noise are clearly observed when fingers slide on surfaces with isolated protruding features [3].
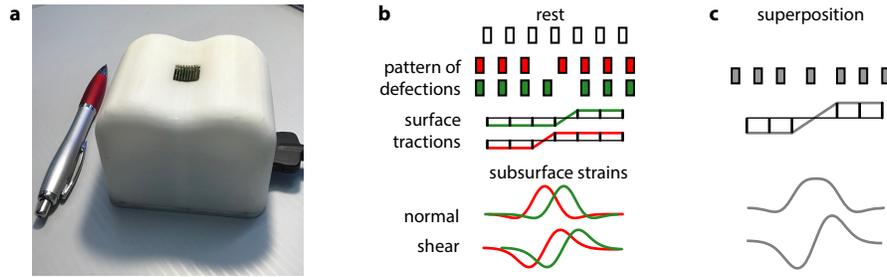

Fig. 2. Stimulus production. **a**. Tactile display with a 10 mm by 10 mm active surface described in greater detail in reference [30]. **a**. Two adjacent virtual edges (red and green) created by the local traction given by deflecting traction surfaces differentially. **c**. The superposition of two adjacent edges is equivalent to a wider edge.

2.2   Stimuli

To realise a moving version of the stimulus shown in Fig. 2, let p_i be the deflection of the i-th traction surface, the command sent to an entire column of traction surfaces was,

$$p_i(t) = (-1)^i \sin(2\pi f t) \frac{1}{2\pi\sigma} \exp\left(-\frac{iw - vt}{2\sigma^2}\right),$$

where f is the frequency of the modulation, t is time, σ encodes the width of the edge, w is the spatial period of the display, and v the speed of the stimulus. Here we selected, $f = 30$ Hz, $\sigma = 1$ mm, $w = 1.2$ mm, and $v = 2.0$ mm/s. Accordingly, the deflections needed to generate the test stimuli of Fig. 1 were,

$$d_i(t) = \begin{cases} p_i(t) & i = 0, 1, 2, \\ 0 & i = 3, 4, \\ p_i(t - g/v - \delta) & i = 5, 6, 7, \end{cases}$$

where g is the size of the gap and δ the delay. Seven conditions were tested by stetting $g = 2.0$ mm and by randomly drawing δ from the set $\{0.0, 0.16, 0.33, 0.50, 0.66, 0.83\}$ s.

2.3 Participants

Participants were eight volunteers (23–63 years old, 5 male, 3 females) including two of the authors. With the exception of the authors, the participants did not know the purpose of the experiment and they had never experienced the stimuli. All the subjects were right handed. Except for the authors, they did not know the purpose of the experiment and they had never experienced the stimulation presented to them. Participants gave informed consent.

2.4 Protocol

We employed the method of the single stimulus because it is well adapted to testing our experimental question. In this method, participants are presented with randomised stimuli that vary parametrically in an interval of values which they compare to an implicit standard [22]. The single stimulus method competes with the staircase method in terms of the speed at which the results can be obtained and has the advantage to probe the whole stimulus range.

A session comprised seventy randomised trials, which consisted of ten trials for each condition, five were started from right, five are from left. A trial, including the answer, took less than ten seconds. During testing, the participants heard pink noise through headphones to reduce distraction and to prevent them from using cues arising from faint noises emitted by the display device. They were allowed to take a break at their discretion at any time during the experiment.

The participants used the index of their dominant hand. They were asked to answer the question "Does the stimulus have a spatial gap or not?". The size of the gap was not specified. Participants easily answered the question after a few trials. There was no need for a familiarisation session.

3 Results

Figure 3a shows the overall psychometric curve for the answers pooled across all participants. Error bars show the standard deviations. While all participants produced similar thresholds, there was a large dispersion in their perceptual sensitivity (or in the d's, to use signal detection terminology).

Two illustrative examples of individual results are shown in Figs. 3b and 3c showing similar thresholds but different sensitivities. This result is not surprising given that the participants were exposed to novel, non-physical stimuli, which they never experienced before. It is likely that individual observers appealed to different criteria to decide that there was a gap or not in what they felt.

However, with the exception of one participant, all other participants had a low probability of detecting a discontinuity in the stimulus when the 2.0 mm gap was traversed in less that 0.2 s while they all performed ideally when the gap traversal duration was at its rightful 1.0 s.
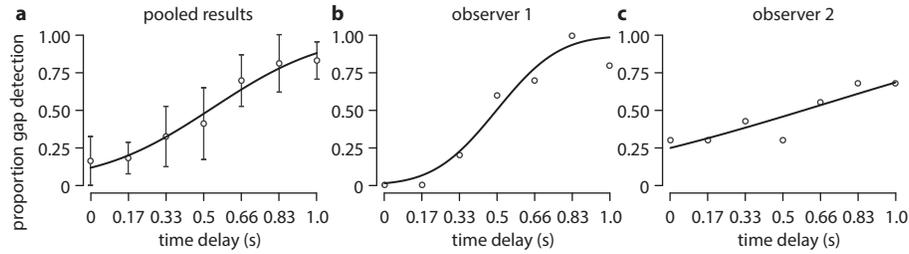
Fig. 3. Results.

4   Discussion

In touch, it is known that our perceptual system has a tendency to relocate tactile stimuli in external space when the relative movement of the stimulus on the skin co-occurs with limb movement [35, 32, 23]. While it could be tempting to explain the observed effect by the relocation of the third portion of the stimulus in external space, these effects are unlikely to be related to the completion effect observed here and by Seizova-Cajic and Taylor because of the absence of limb movement, voluntary or not.

Another family of effects, here collectively termed "space-time interactions", are more likely candidates for being related to the completion phenomenon at hand [10, 16, 34, 5, 2, 11, 8]. Goldreich unified the 'contraction of space' and the 'dilation of time' common to all these effects into instances where our perceptual system makes judgments about the motion of object based on the prior assumption of a standard, expected velocity weighted by sensory evidence [12].

It is appealing to explain what we observed as a type of space-time interaction, but such an explanation is inadequate on two counts. Previously reported time-space interactions are all variants of an apparent motion effect where the loci of stimulation are separated in space. On the other hand, it is known that the discretisation of a signal, in time or in space, amounts to introducing an infinite amount of uncertainty since the reconstruction of the original signal requires strong prior assumptions. For example, the spoked wheels of wagons can be seen to turn backward in movies. Such percepts can be explained by the violation of the conditions of application of the Nyquist-Shannon sampling theorem leading to the apparition of negative frequencies.

Here however, as in Seizova-Cajic and Taylor's experiments, the signal was continuous. One other aspect that the perceptual space-time interactions effects cannot explain is the fact the gaps are perceptually abolished when the delay is zero. This limit case cannot be not asymptotically predicted by space-time interaction models. Neither can those models explain another interesting mislocalisation illusion described by Brugger and Meier which also uses a continuous sensory input [4]. Other explanations for the elimination of the spatial gap could appeal to a "filing-in" phenomenon where contextual information is felt within the missing portion of the stimulus or to the "disappearance" of a portion of our somatic representation. These and other phenomenological explanations drawing from Gestalt organisational principles are carefully examined by Seizova-Cajic and Taylor [28].

At this point, the authors believe that an explanation for the perceived reduction and obliteration of gaps traversed at abnormal speeds could arise from an Occam's razor, falsifiable, explanatory model. Such model belong to the category of "top-down" models where conscious sensations are, in essence, predictions made by the brain based on previous exposure to sensory inputs. More formally, such models describe percepts as categories of causes for sensory inputs. 'Analysis by synthesis' to use earlier terminology [25], or 'predictive coding' to use more recent terminology [9], amounts to describing perception as a process that minimises the prediction error allowed by short term sensory inputs, on the basis of long term learning. Such models have already been expounded in the visual domain [1, 24, 18].

All of us have been exposed to moving stimuli on the skin and we are very good at detecting them for a large range of velocities, in all regions of the body and particularly in our manipulative extremities. During our development, the neural representations of these stimuli were also associated to other neural representations of the objects that gave rise to them. None of these tactile objects, however, ever jumped through space at infinite speed. When exposed to such novel stimuli, there is no neural representation for them, but ordinary continuously moving objects are those that minimise the prediction error. Such a model remains to formalised, possibly through a Bayesian approach, but can be tested. It would predict, for instance, that prolonged exposure to jumping stimuli, concurrently with some other source of information, say visual, would enable observers to actually feel the spatial extent of zero-delay gaps.

In closing, the perceptual phenomenon discussed here has obvious applications for the development of tactile display technology and informs us of useful constraints about artificial tactile stimuli generation. It is also a good candidate as a test for the evaluation the somatosensory function employing well-controlled stimuli that benefit from high functional significance. Such tests are also amenable to protocols that are convenient to administer since the responses to the questions put to observers refer to whether or not an obvious feature can be detected.

To gain additional insights about the underlying mechanisms, it will be also important to study this new form of perceptual completion with stimuli elicited by advanced electro-tactile displays [33].

5   Acknowledgements

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