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Active touch does not improve sequential processing in a counting task

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Abstract. Active touch involves tactile and proprioceptive sensory inputs, activation of the motor system and executive functions. It has been shown by the previous literature that active touch facilitates shape recognition. Since both active and passive exploration requires sequential presentation of the tactile inputs, this facilitation may be due to the improvement of the sequential-processing mechanism. The effects of active and passive touch on the sequential processing of tactile inputs were tested at different stimulus-presentation rates in a counting task. Active touch did not improve the performance, which shows that the additional sensory and motor information conveyed by active exploration are not utilized by the sequential-processing mechanism. Therefore, the results cannot be explained by the feature-specific theory of sequential processing. On the other hand, the counting errors were higher than those predicted by the limitation of the minimal inter-stimulus interval, which is suggested by the central-timing theory. Consequently, it is proposed that a mechanism based on the central-timing theory may contribute to tactile sequential processing, but the bottleneck at high presentation rates is probably due to short-term memory.

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INTRODUCTION

Sequential processing of sensory inputs has been studied typically in relation to temporal order judgment. Two main theories have been proposed to explain the perception of temporal order of sensory events: the central-timing theory and the feature-specific theory. Pöppel (1997) argued that the functional states of temporal perception are implemented by neuronal oscillations with approximately 30-ms durations, which is a limitation imposed by the central-timing theory. Many human studies support this hypothesis which implies a mechanism independent of sensory modality. Temporal-order thresholds are approximately the same for auditory, visual, and tactile stimuli (Hirsh and Sherrick 1961). For example, at about 40-ms inter-stimulus interval, the temporal order of auditory and visual stimuli can be judged with high (i.e., 75%) correctness (Kanabus et al. 2002). On the other hand, if stimulus properties are varied substantially, e.g., auditory tones versus clicks, feature-specific mechanisms may also arise. The feature-specific theory suggests that additional sensory cues have significance in perception (Fink et al. 2006).

The sense of touch, unlike some modalities (e.g., hearing), allows easy control of the active or passive presentation of sensory stimuli (Gibson 1962). In passive touch, the stimulus is presented on a stationary skin surface. Active touch, however, consists of active motor exploration of mechanical stimuli with the willful movement of a skin surface. Therefore, in addition to the excitation of tactile receptors, active touch involves the activation of the proprioceptive system (not consciously perceived), the motor system and also higher-order executive functions. Active touch is superior to passive touch for shape recognition (Heller 1984, Heller and Myers 1983), and produces higher size estimates on glabrous skin (Bolanowski et al. 1999). However, active touch and passive touch are equally effective for pattern recognition if the stimulus pattern is smaller than the finger pad (Vega-Bermudez et al. 1991), for texture perception (Lederman 1974), and for roughness estimation (Verrillo et al. 1999). The goal of this study is to investigate the effects of active touch on sequential processing. Because both active and passive exploration requires sequential presentation of tactile inputs, the facilitation by active touch may be due to the facilitation of sequential processing. Furthermore, it may be hypothesized that if a mechanism based on the central-timing theory dominates sequential processing, additional sensory cues contributed by active touch should not improve the performance. However, a mechanism based on the feature-specific theory is more likely to be affected by active touch. The paradigm to test these hypotheses is based on counting supra-threshold tactile inputs presented sequentially. By varying the presentation rate of the stimuli, it is also possible to test the minimal inter-stimulus interval which is assumed to be about 30 ms. Although stimulus recognition and counting may be not directly related, sequential stimuli need to be first discriminated and the numerosity is most likely determined before a judgment can be made about recognition.

METHODS

Participants

Five male and five female healthy human subjects volunteered to take part in the study. The mean age of the subjects was 23 (range: 19–27). Nine subjects declared they were right-handed; one subject declared he was left-handed. The experiment does not pose any harm and it adheres to the US National Institutes of Health ethical guidelines for testing human subjects. The subjects were university students recruited locally and they gave written informed consents. None of the subjects had dermatological or neurological problems that could interfere with the tactile experiments. The subjects were blindfolded during the experiments, and the tactile stimuli were applied on the right or left index fingertips of the subjects according to handedness, which was determined by self-report.

Apparatus

Three smooth wooden sticks were prepared with 8, 10, or 12 nails, which were randomly placed along the long axes of the sticks within 1-m distances (for 10-nail stick at 37, 44, 55, 57, 62, 69, 70, 79, 84, 96 cm). Each nail head was a tactile stimulus to be applied on the fingertip. Scanning a finger tip across the stick (or *vice versa*) sequentially presented supra-threshold tactile stimuli to each subject. The stick was secured in a wooden housing to allow for either active scanning by the subject or for passive touch. During passive touch experiments, the experimenter presented the stimuli to the subject by sliding the stick within the housing below the finger. In this condition, the finger was immobilized on the edge of the housing by tape. The subjects maintained contact force in the range of 100–200 g with the stick surface, which was measured by a digital balance (model 440-49N; Kern & Sohn GmbH, Germany). The average scanning speed was measured by a custom-made electronic counter circuit. The subjects (and the experimenter for the passive condition) were trained in four speed ranges. The scanning surfaces had additional areas with no tactile items on either end, which allowed for the acceleration/deceleration of the finger. The speed ranges were 21–24 cm/s (slow: S), 33–40 cm/s (medium-slow: MS), 51–65 cm/s (medium-fast: MF), and 80–95 cm/s (fast: F). The average scanning speed was monitored for each trial. If the speed did not fall in the prescribed range for a given trial, that trial was repeated at the end of the session. Subjects' faces were always oriented towards and perpendicular to the scanning surface, because this was reported to be important for tactile perception (e.g., see Tipper et al. 1998).

Design and Procedure

The experiment was based on a 4 × 2 × 3 factorial design. The first two factors were the presentation rate (i.e., scanning speed: S, MS, MF, F) and the presentation mode (passive touch, active touch). The number of tactile stimuli (8, 10, 12) was varied to eliminate learning effects. The number of tactile stimuli was always unknown to the subjects. The presentation modes were tested in two blocks. The scanning speed and the number of tactile stimuli were randomized in each block. Each subject was tested four times for every condition in a given block. The subjects were instructed to count the tactile 'bumps' on the sticks during scanning the surface of each stick. Internal verbalization was not suppressed during the trials. In the active presentation mode, the subjects were instructed to scan their fingers by themselves. In the passive presentation mode, their index fingers were held steady, and the experimenter moved the stick which sequentially applied the tactile stimuli. The subjects were expected to recall the number of tactile stimuli immediately after scanning. Each experimental session took 1–2 hours with breaks in between. Each subject was tested in one separate session, and the experiment was completed in 10 sessions.

Analysis

For each experimental condition, four responses were obtained from each subject. After the experiment, the subjective counts of each subject were plotted as a function of the trial number, and no learning effects were found (not shown). The estimated counts for the number of presented stimuli were averaged. The average estimation error was normalized with respect to the actual number of stimuli (i.e., 10) to yield the relative error. The effects of the scanning speed, the presentation mode, and the number of stimuli were studied by using a 3-way ANOVA with 10 replications (i.e., 10 subjects). The correlation between the scanning speed and the relative error was found. The statistical analyses were performed in MATLAB (The MathWorks, Inc., Natick, MA). The error bars in the plots are the standard errors of the mean.

RESULTS

The subjective counts for all stimuli were initially analyzed by using a 3-way ANOVA with 10 replications. There was no interaction between the three factors and between the pair-wise combinations of them (all Ps>0.680). There were highly significant main effects due to the scanning speed (F=118.88, df=3, P<<0.001) and the item number (F=12.69, df=2, P<<0.001). There was a significant, but to a lesser degree, effect due to the presentation mode (F=6.34, df=1, P=0.013). However, the difference between the active- and passive-touch conditions was not statistically significant in the data pooled over the remaining two factors (two-sample t-test; n=120, P=0.115). On the other hand, the average counts decreased as a function the scanning speed (S: 7.0, MS: 5.9, MF: 4.8, F: 3.6) and increased as a function of the item number (8 items: 4.9, 10 items: 5.3, 12 items: 5.8). Since the subjective counts increased relatively less than the number of stimuli, the relative errors also increased (more negative) as a function of the number of stimuli.

For brevity, only the relative errors for the 10-item condition are plotted as a function of the scanning speed (Fig. 1). It is important to note that the average relative errors are always negative, which indicates that the subjects underestimated the number of tactile stimuli. The relative errors increased as the scanning speed was increased. There is a significant and high negative correlation between the scanning speed and

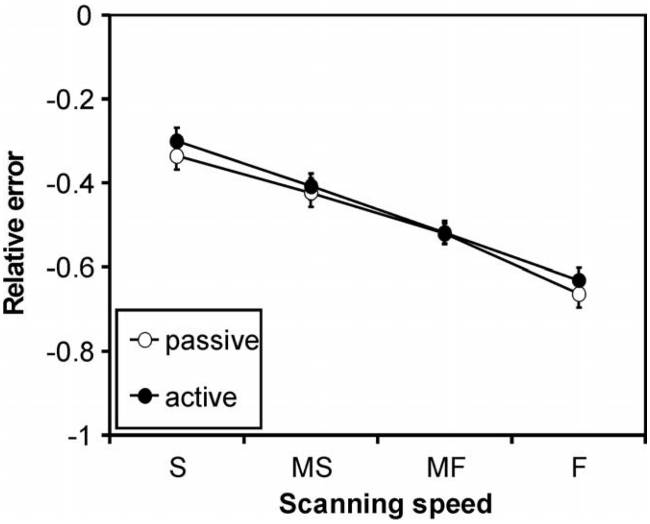

Fig. 1. Relative counting errors as a function of the presentation rate (scanning speed). The presentation mode (active and passive) is presented as the parameter. (S) slow; (MS) medium-slow; (MF) medium-fast, (F) fast (see text for details).

the relative errors in both active and passive scanning for the 10-item condition (active: $r = -0.803$, $P<0.001$; passive: $r = -0.786$, $P<0.001$). Additionally, there was no interaction between the scanning speed and the presentation mode ($F=0.125$, df=3, $P=0.945$). There was a significant main effect due to the scanning speed ($F=42.367$, df=3, $P<0.001$) as it was expected from the correlation analysis. However, there was no significant difference between active and passive scanning ($F=0.962$, df=1, $P=0.330$).

Post-hoc analysis of the distribution of the tactile stimuli on the 10-item scanning surface revealed the following inter-stimulus distances: 7, 11, 2, 5, 7, 1, 9, 5, and 12 cm. The 30-ms minimum inter-stimulus interval would impose the following maximum counts for S, MS, MF, and F scanning speeds respectively: 10, 9, 9, 8. Therefore, the corresponding relative errors would be 0, –0.1, –0.1, and –0.2, respectively. The relative errors (see Fig. 1) were much higher than the relative errors that would be caused by the limitation of the minimum inter-stimulus interval in all experimental conditions ($n=10$ for each condition; one-tailed t-test, all Ps<0.001).

DISCUSSION

In this study, active and passive processing of tactile inputs was tested at various scanning speeds and no difference was found between active and passive touch. This shows that the additional sensory input during active touch does not improve sequential processing and suggests that the mechanism based on the central-timing theory may dominate over the mechanism suggested by the feature-specific theory in this condition. However, the performance decreased significantly as the scanning speed increased, and the counting errors were much higher than those expected by the limitation of a minimal inter-stimulus interval. Therefore, the bottleneck in the sequential processing of tactile inputs may possibly be related with short-term memory, and cannot be explained by the central-timing theory. On the other hand, improved tactile shape recognition during active exploration reported in the literature may be due the facilitation of tactile imagery, but probably not due to improved sequential processing.

Active scanning

It is also important to note that the attentional resources allocated for the active-touch task presented here are greater than those allocated for the passive-touch task, because the subjects were required to maintain the scanning-speed range in the active touch. This factor might have decreased the performance in the active-touch condition. However, it would be difficult to control active-scanning speed and also obtain a natural setting for tactile exploration to eliminate the attention factor entirely.

Counting task

The tactile counting task used in the experiment presented here always resulted in negative average errors. That is to say, the number of the tactile stimuli was underestimated. This is consistent with numerosity judgments for tactile stimuli distributed over the body surface (Gallace et al. 2006). Counting is considered to be different from subitizing, which is the very fast and accurate enumeration of small groups of four or fewer objects, based on behavioral (e.g., Trick 2005) and electrophysiological (e.g., Nan et al. 2006) data. Imaging studies show that both enumeration processes, however, utilize a common neural network in intraparietal areas (Piazza et al. 2002). These areas are among the brain regions associated with the abstract representation of quantity and mental calculations (Dehaene et al. 2004). Note, however, that most of the studies to date have used visual stimuli in a counting task. The recent study by Gallace and others (2006) suggests that subitizing actually does not occur for tactile stimuli. The experiment presented here may also be helpful to improve the cognitive models of counting.

CONCLUSIONS

Active and passive sequential processing of tactile inputs was tested in a counting task. In contrast to the prediction of the feature-specific theory of sequential processing, additional sensory inputs during active scanning did not improve the performance. Furthermore, the bottleneck in sequential processing is possibly governed by short-term memory.

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