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Spatial perception of textures depends on length-scale

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***Abstract*— This study explores the ability to sense, retain, and recall tactile textures with and without deliberate visuospatial distraction. By examining this tactile recall for textures with significantly different characteristic length scales, we aim to distinguish modes of textural processing that are differentiated with respect to the use of spatial working memory. All textures were produced on a glass panel where ultrasonic vibrations modulated the friction between glass and the user's finger. The goal of this study is to demonstrate that spatial working memory is a significant tool in representing textures with relatively large inter-feature spacing, but does not appear to play a large factor when textures have relatively small inter-feature spacing. This conclusion suggests that spatial information is only relevant in texture sensation above a certain length scale, which could contribute to the reduction of information required for a texture to be realistically reproduced in a virtual setting.**

I. Introduction

The nature of tactile perception, in particular the distinction of sensing modes between fine and coarse textures, has a long history of research. In 1925, David Katz proposed what was later termed the *duplex theory of texture perception*: both spatial and temporal (vibratory) cues contribute independently to texture perception [8]. Later research demonstrated that these temporal cues relied upon finger movement to generate fingertip vibration, while spatial features required no such movement [7], lending evidence to the concept that two independent sensory schemes are responsible for detecting the spatial and temporal aspects of physical textures.

Specifically, the research of Hollins et al. [7] noted that spatial cues gave very little discriminatory ability to so-called *fine* textures (particle sizes below 20 micrometers), evidenced by poor discrimination performance when testing textures with a static touch. This ability was greatly boosted, however, by the addition of finger movements (which produced temporal cues via finger vibration). This is in contrast to detection of so-called *coarse* textures (particle sizes above 100 micrometers), which was comparable during both static and dynamic touch. In another study [6], sensitivity to temporal cues was decreased via vibrotactile adaptation, which resulted in a drop in discriminatory ability to fine textures, but no effect to this ability for coarse textures. Below a certain threshold of feature spacing, it would seem, temporal cues dominate texture perception, whereas spatial cues are more important above this threshold.

Since then, several benchmarks have been set for the boundary between fine and coarse textures with respect to the nature of their perception. Estimates on the lower bound of spatial tactile acuity include 1.6 mm [10], 0.25 mm [9], 0.8 mm [4], and 1.0 mm [13].

This boundary marks the point at which spatial information is no longer processed during perception. Such information discarding is of particular use in the design of virtual textures: fine textures can be represented in a purely temporal manner (e.g., as a sum of sinusoids with randomized phase), without producing any detectable difference to the user. The discarding of spatial data represents a significant decrease in the informational load of storing such a virtual texture.

The ability to compare two textures explored by touch necessitates the existence of some texture representation in human memory. The Working Memory model, first proposed by Baddeley and Hitch in 1974 [1], remains a leading explanatory schematic of the link between perception and memory. Succinctly, the model describes an internal *central executive* that redirects sensory input to one or more independent systems for temporary storage.

At the model's conception, these systems included the *phonological loop*, governing information stored via subvocal rehearsal (such as speech or rhythmic patterns); and the *visuospatial sketchpad*, capable of storing information in a spatial format.[1] Importantly, these

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[1]We note that while the term *visuospatial sketchpad* suggests exclusively visual inputs, this component could constitute a more general form of spatial working memory, compatible with non-visual sensory modalities.

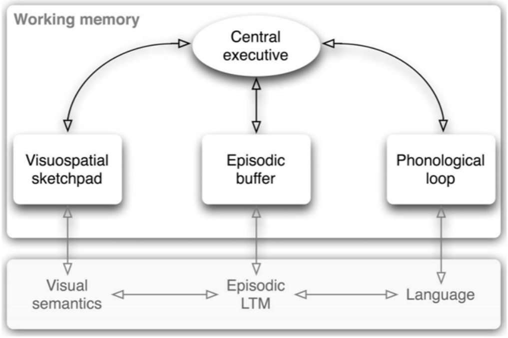

Fig. 1. Baddeley and Hitch's modern model of working memory, reproduced from [12]

systems are susceptible to independent suppression. Further research has demonstrated methods to interfere with these systems, such as articulatory suppression preferentially affecting the phonological loop [2] and spatial imagery affecting the visuospatial sketchpad. Articulatory suppression typically requires the test subject to verbally repeat a sequence of meaningless syllables, competing with the inner phonological loop used to retain verbal or rhythmic information in working memory. Spatial imagery distracting is exemplified by the Brooks Matrix Task, which requires memorizing a spatial array of numbers and later recalling the numbers stored at specific locations [3].

An extensive body of research has investigated visual and auditory stimulus within the framework of working memory, but the analogous pathway of tactile information remains rather unknown. It is logical to surmise that, given the demonstrated duplex theory of texture perception, there exist similarly dual modes of representing textures in memory. Due to the demonstrated importance of spatial information in textures with wide feature spacing, in contrast to the diminished importance of spatial information in textures with narrow feature spacing, we argue that the visuospatial sketchpad is a likely candidate for a working memory system that is effective for some, but not all, textural stimuli.

While earlier studies have demonstrated aspects of tactile perception that indicate the dominance of spatial and non-spatial cues for coarse and fine textures, respectively, this is the first study, to our knowledge, that directly relates length-scale-specific perception to spatial working memory. The demonstration of selective discrimination suppression of textures with a longer length scale using a spatial distractor represents both a novel mode for controlling texture perception and suggests a previously-untested pathway for texture representation within human memory.

II. Experimental Design

A. Overview

To study tactile perception at varying length scales with and without the effect of spatial working memory distraction, a test was designed with the following properties. 40 total test trials were presented to the subject, each requiring the subject to confirm whether two touch-explored virtual textures were identical or different in some way. The first 8 trials were considered training trials, and the subsequent 32 regular trials were recorded for results, divided evenly into four groups: 1.) large feature spacing without spatial working memory distraction, 2.) large feature spacing with distraction, 3.) small feature spacing without distraction, and 4.) small feature spacing with distraction. Exactly half of the trials presented different textures to the user, while the other half presented identical textures (as control).

B. Subjects

There were 24 test subjects, 16 males and 8 females, median age: 28 years. Subjects used a single finger of their choice to interact with the stimulus surface throughout the duration of testing, after pre-test training allowed them to try several fingers to find the strongest sensation. Subjects were offered payment for participation.

C. Apparatus

Virtual textures were displayed using a TPad surface haptics device (pictured in Figure 2). Using infrared position sensing and the vibration of a glass surface at ultrasonic frequencies (resonant frequency: 31170 Hz), horizontal-position-dependent reduction of friction can be achieved between glass and the user's finger, proportional to the amplitude of applied vibrations [11] [14]. The active length of the glass surface was approximately 100 mm with location sensing resolution of 0.0053 mm. Finger position in the height dimension (10 mm) was not sensed. By modulating vibration amplitude of the glass screen, finger/glass friction is controlled. Subjects explored virtual textures by sliding a finger left and right across the length of the surface. Friction maps were programmed and commanded over USB using a Microsoft Surface Pro 4 tablet running MATLAB R2019b. This tablet was also used to record test subject responses and advance test trials.

Fig. 2. High-Performance TPad surface haptics device

D. Stimuli

Pilot testing indicated that, for average inter-feature distances below 5 mm, subjects could not reliably distinguish textures of equal average inter-feature distance with different individual feature placements. As a spatial rearrangement of textural features is imperceptible at this length scale, it can be concluded that this specific family of textures at this characteristic length scale does not provide spatial information during perception. Above average inter-feature distances of 10 mm, however, textures with rearranged feature placements were reliably identifiable by subjects. By the same reasoning, this characteristic length scale must provide some spatial cues during perception. To target an average (non-distracted) texture discrimination performance of approximately 75% correct, subjects were asked to make same/different judgments between either: 1.) two textures with average length scales of 13.5 mm (wide spacing), or 2.) one texture with average length scale of 2.5 mm and one with an average length scale of 4.6 mm (narrow spacing). In both cases, the ”same” condition represented the first texture being displayed twice.

All textures were composed of several 2.6 mm-long patches of minimum friction separated by varying-length patches of maximum friction. (See Figure 3.)

One pseudorandom texture of each inter-feature distance was generated by pulling several integers from a uniform distribution to assign inter-feature distances. The center of each distribution was equal to either 13.5 mm, 2.5 mm, or 4.6 mm. The width of each distribution was equal to twice its center, so that each distribution covered integers from 0 to twice its center. In this way, the three textures approximated scaled versions of each other, having equal width-to-center ratios for the uniform distributions from which the inter-feature distances were drawn. For each texture length scale, one virtual texture was produced by placing fixed-length minimum-friction features between patches of varying-length maximum-friction patches, the lengths of which were pulled from the distributions described above. (See Figure 3).

The three textures as produced by the process above were given random rearrangements to produce additional pseudorandom textures. The order of inter-feature distances was shuffled, producing a different texture with inter-feature distance mean and standard deviation identical to the original texture. In this way, 64 unique textures were created.

E. Main Task and Distraction

The main task of the experiment was to compare two virtual textures presented at different times and decide whether they were identical matches with one another or different in the arrangement of fixed-length features.

Spatial working memory suppression was achieved using a technique derived from the Brooks Matrix Task. A 4-by-4 matrix of cells was presented to the user with five arbitrary cells containing five pseudorandom integers between and including 1 and 9. Two integers of the same value were never displayed in the same matrix. To apply a similar visual load with the distracted condition, during the non-distracted (control) condition, this matrix was completely filled with the digit 1, and test subjects were informed that a fully-filled matrix would always only contain the digit 1. In this way, a similar amount of visual information was displayed, without requiring any significant load on spatial working memory.

Due to the competing nature of the texture discrimination and spatial working memory distraction tasks, it is possible that subjects may ignore the main task in favor of performing well on the distraction task. As the purpose of the study is to investigate the effects of distraction on main task performance, subject data were considered outliers if the number of main task errors exceeded two standard deviations from the population mean without any increase in distraction task errors.

Test subject input was recorded using the tablet PC containing the TPad texture data. A simple GUI

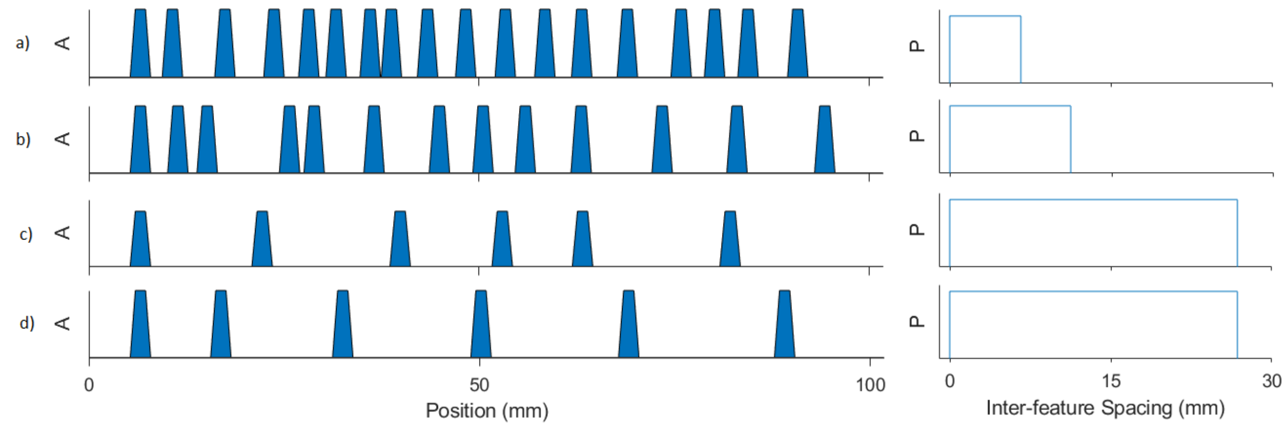

Fig. 3. Sample texture maps and corresponding probability distributions for three values of average feature spacing: 2.5 mm (a), 4.6 mm (b), and 13.5 mm (c) and (d). 'A' represents normalized TPad friction reduction amplitude, and 'P' represents normalized probability amplitude. (All probability distribution widths are twice the given average feature spacing.) Note that, during a trial with the *different* condition, texture (a) and texture (b) would be compared for the narrow spacing group, and texture (c) and texture (d) would be compared for the wide spacing group.

(pictured in Figure 4) was designed that allowed test subjects to view the current phase of the test trial and the trial number, to view the distractor matrix as well as an indication of which number to recall, and to input decisions in both the texture discrimination task and matrix distraction task. Test subjects used the touchscreen interface to input decisions. Test subjects were required to use one finger for all TPad touch interactions but had the freedom to use any finger on any hand to input touch input into the tablet PC.

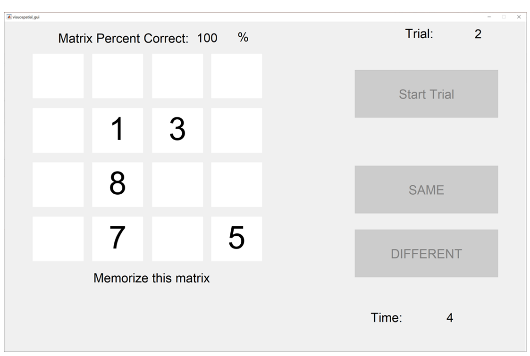

Fig. 4. Graphical User Interface (GUI) presented to test subjects

F. Experiment

Test subjects were introduced to the TPad device and allowed to freely explore four sample textures for approximately five minutes. Sample textures consisted of friction maps not used in the experiment and were designed for the purpose of confirming that test subjects were able to detect friction changes when swiping a finger across the TPad glass surface. Following this, subjects were introduced to the GUI and given instructions for the test, at which point they were allowed to begin. Including sample texture exploration, total testing time per subject was approximately 40 minutes.

For each of 40 trials the following procedure was followed. The test subject started the trial and the first texture was produced on the TPad surface, allowing the subject to inspect it freely for 10 seconds. Following this, the TPad surface was turned off and the distractor matrix was displayed for 10 seconds. Next, the distractor matrix was hidden, and the second texture was produced on the TPad surface, allowing the subject to inspect it freely for 10 seconds. After this, the TPad surface was turned off and the subject was prompted to answer the first question: were the two textures displayed exact copies, or different in the arrangement of fixed-length features? Upon answering, the test subject was prompted to answer the second question: what was the number contained in a single indicated cell of the matrix? (For non-distracted control trials, where all cells in the matrix contained the number 1, all cells were indicated during this decision prompt). This ended the trial.

III. Results

The average number of errors made by subjects in the main task (texture discrimination) was 10.63, standard deviation: 3.36 (as compared to 16 errors or 50% expected by chance). The average number of errors made by subjects in the distractor task (matrix recall) was 2.04, standard deviation: 1.83 (as compared to 14 errors or 89% expected by chance, given that there were 9 choices). A weak negative trend between main task errors and distractor task errors was observed (R^2 = 0.0747). This effect is consistent with dual-task inteference; that is, an increase in attention to one task would reduce attention to the other.

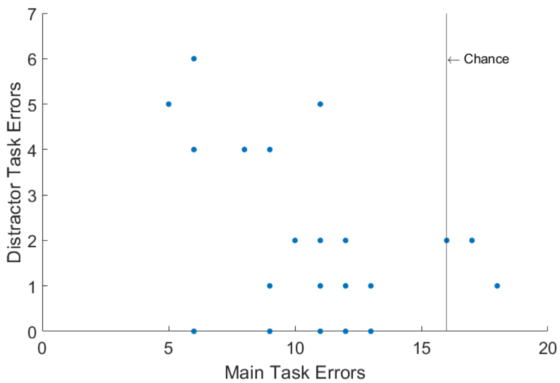

Fig. 5. Subject performance in Main Task (texture discrimination) and Distractor Task (matrix recall). Vertical line indicates performance at chance for Main Task.

Two subjects exhibited especially low performance in the main task, with main task errors of 17 and 18. These subjects performed well in the distractor task, with distractor task errors of 2 and 1, respectively. This main task performance, below the level of chance, was near two standard deviations from the mean performance computed using all subjects. Given the pattern of the data, we conclude that these two subjects devoted nearly all concentration to the distractor task at the cost of the main task, resulting in chance main task performance and high distractor performance. As the purpose of this study is to investigate the effects of distraction on main task performance, we consider these two subjects outliers and remove them from the analysis below.[2] The texture discrimination performance among the remaining 22 subjects was sorted into four categories along two variables: *Wide* or *Narrow* feature spacings (corresponding to 13.5 mm and 2.5/4.6 mm textures, respectively) and *Control* or *Distracted* trials. The average performance in each of these categories is shown in Figure 6.

Univariate Type III Repeated-Measures ANOVA (assuming sphericity) was performed using the R programming language to identify the significance of the interaction between texture length scale (*Narrow* or *Wide*) and Distraction (*Control* or *Distracted*) on texture discrimination performance. The results are shown in Table 1.

[2]If the two outlier subjects are included, the ANOVA indicates a lack of power to detect the interaction (p = 0.139), but the t-test comparing distractor to control yields the same effects: nonsignificant for narrow textures (p = 0.198) and significant for wide textures (p = 0.007).

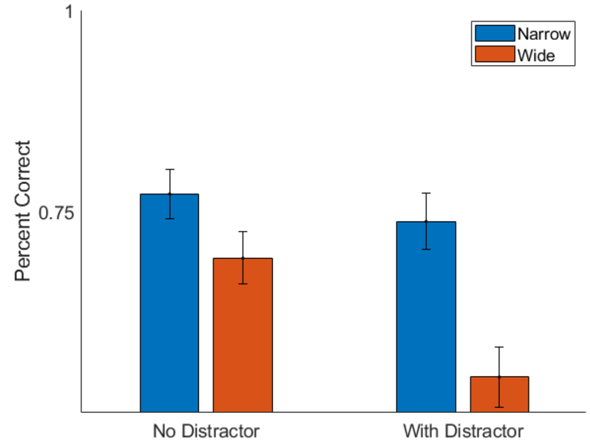

Fig. 6. Average texture discrimination performance for each of two texture scales, with and without distractor. Bar: average performance; whisker: standard error of the mean

TABLE I

REPEATED-MEASURES ANOVA RESULTS

	Sum Sq.	Error SS	Df	F	p-value
Length Scale	26.18	48.82	21	11.26	0.003
Distraction	11.64	30.36	21	8.05	0.010
Interaction	4.55	17.46	21	5.47	0.029

IV. DISCUSSION

The results demonstrate that suppression of spatial working memory decreases performance in texture discrimination significantly for wider inter-feature spacing but not for narrower inter-feature spacing. The distractor produced a 14.8% drop in average performance for wide textures, as compared to a nonsignificant 3.3% drop for narrow textures.

These results are in line with the duplex theory of texture perception, confirming that widely-spaced features in a texture rely heavily on spatial cues during perception, while narrowly-spaced features do not. To our knowledge, however, the connection between this theory and the concept of dedicated working memory components has not yet been established. By demonstrating that the spatial working memory is a key to storing widely-spaced textures in memory only, we reach two novel conclusions. First, we suggest that the perception of widely-spaced textures, while tactile in origin, is converted to a spatial format in its cognitive representation. Second, we note that the perception of narrowly-spaced textures, while affording discrimination performance well above chance, must rely on some other non-spatial memory representation, potentially used for retention of temporal aspects of tactile perception. This would be consistent with the assumption that fine textures are coded by the neural system as a vibrotactile signal.

The existence of a length-scale-governed threshold between textures that make use of the visuospatial sketchpad and those that do not will give guidance to future designers of virtual textures. By enforcing feature density to remain above this threshold, a designer can be confident that spatial information is not being perceived by the user and can be safely discarded without risking any perceptual difference. This high-information-load spatial data (e.g., exact location of each textural feature) can be replaced with a temporal representation of the texture (e.g., given a mean and standard deviation of feature spacing within a given area, features placed stochastically) that can be stored using significantly less information.

It is not necessary to our conclusions that the specific model of working memory described by Baddely and Hitch be accepted. For example, a competing theory described by Cowan [5] rejects the existence of several specific-purpose short-term memory subsystems in favor of a limited-capacity focus of attention. In this model, the Focus of Attention, capable of storing a small number (typically 3-5) of cognitive items, is directed voluntarily and involuntarily by a Central Executive. The phenomenon of short-term memory is apparent in the finite lifetime of Activated Memory, where, without the rehearsal provided by the Focus of Attention, storage lasts on the order of seconds. To accommodate results like these that show modality-specific interference, this model would have to be augmented with another mechanism, for example, modality-specific application of the Focus of Attention.

Future work will help elucidate the means by which non-spatial tactile information is stored in working memory and develop a suppression technique for this segment analogous to articulatory suppression or visuospatial distraction. Additionally, perceptual interaction effects will be investigated when tactile features of both *narrow* and *wide* length scales are present simultaneously. Taking auditory perception as inspiration, the masking effects of tactile features is an area of great interest towards the goal of efficiently compressing virtual texture representations.

Acknowledgements

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