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Haptic banknote design

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Introduction

New developments in printing technologies have made it possible to create intaglio structures of enormous richness in fine spatial details. Nowadays relief height of printed intaglio structures can reach up to 50–100 microns thereby creating not only visual, but also strong and significant tactile and haptic sensations (Fig. 1).

FIGURE 1.
Example of an artificial banknote exemplifying the richness and visual details created by intaglio printing.

Measures to prevent counterfeiting: safety features

Since the introduction of banknotes centuries ago, banknotes were counterfeited. Particularly currencies with wide cross-country distributions are a target. According to "*The United States Treasury Bureau of Engraving and Printing*" (2005) counterfeited notes worth millions of US Dollars are detected year by year with a trend to increase in countries outside the US (Fig. 2).

Using current high-technology features, numerous security-features are integrated in the banknote design to prevent or to impede counterfeiting. Most widely used features are watermarks, security threads, ultraviolet fibres and ink, special foil elements, hologram patches or stripes, glossy stripes and iridescent stripe/shifting colours.

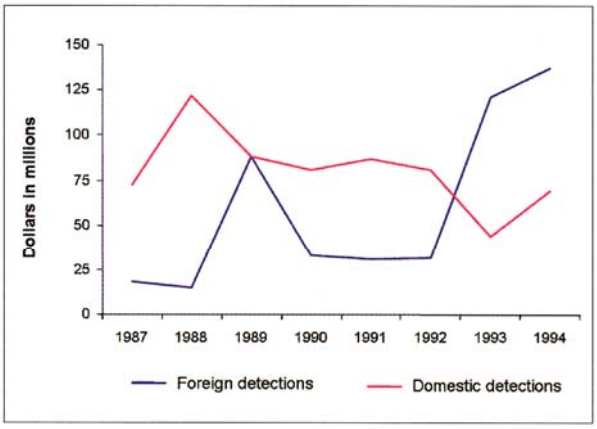

FIGURE 2.
Counterfeit detection of US$ according to data from Secret Service for Fiscal years 1987 to 1994. Source: The United States Treasury Bureau of Engraving and Printing © 2005.

Measures to prevent counterfeiting: tactility

Up to now, design options for banknotes were largely governed by aesthetical and graphical

Box 1

What governs perception in visuotactile stimulation, a situation relevant in banknote handling? Using transcranial magnetic stimulation as a means to induce a so-called 'virtual' lesion during a roughness and distance discrimination tasks in sighted and blind subjects revealed a double-dissociation effect in which roughness and distance are primarily processed in somatosensory and visual cortex, respectively. Low-frequency transcranial magnetic stimulation applied to somatosensory cortex disrupted roughness without affecting distance judgments, while transcranial magnetic stimulation to visual cortex disrupted distance but not roughness judgments indicating that in fact both modalities are involved in this tactile texture perception [1]. In another experiment visuotactile texture assessment consisting of the speeded discrimination of roughened textile samples, was tested in the presence of a congruent or an incongruent textile distractor. When discriminating between samples, visual assessment of textile roughness was modulated by incongruous tactile distractors, but not vice versa, even when visual distractors were more discriminable than tactile targets demonstrating a significant asymmetry in interference [2]. This view is supported by earlier experiments, in which subjects assembled puzzles under different conditions of visual-haptic perception which both separated these perceptual systems and required the simultaneous use of vision and touch. When vision and touch were used simultaneously to examine the same stimulus, and visual information was adequate for responding, vision dominated touch. However, in conditions of visual-haptic perception in which visual input was inadequate for responding or when haptic perception was independent of vision, subjects relied upon a form of information which was specifically tactual in nature and independent of visual or verbal recoding [3]. Using a visuo-haptic virtual reality environment, subjects had to judge the distance between two surfaces based on two perceptual cues: a visual stereo cue obtained when viewing the scene binocularly and a haptic cue obtained when subjects grasped the two surfaces between their thumb and index fingers. The results indicate that subjects recalibrated their interpretations of the stereo cue in a context-sensitive manner that depended on viewing distance, thereby making them more consistent with depth-from-haptic estimates at all viewing distances [4]. These findings suggest that observers' visual and haptic percepts are tightly coupled in the sense that haptic percepts provide a standard to which visual percepts can be recalibrated when the visual percepts are deemed to be erroneous. Combined, converging lines of evidence imply a guiding role of touch as compared to vision, possibly because the assessment of surfaces and textures is more ecologically suited to touch than to vision [2].

criterions. Owing to new printing technologies described above, tactile features based on intaglio structures are increasingly employed as a means to recognise authentic banknotes. Reasons for an increasing use of tactility is that safety features are often unknown to the user, and that in many cases technical devices are required to decode them such as ultraviolet ink.

The use of haptic features becomes immediately apparent in the following scenario: Imagine a person is receiving a banknote which is visually perfectly counterfeited as in case of high-quality colour prints. However, what is missing is tactility and haptic features. Once a person feels such a note with his fingers, the person will be immediately alarmed. The reason is that tactile/haptic information can override visual information (see Box 1).

How tactility is sensed: factors affecting tactility

Intaglio structures of the type described are detected by a set of highly specialised receptors residing in different layers of the skin. They signal variables such as force, pressure, velocity,

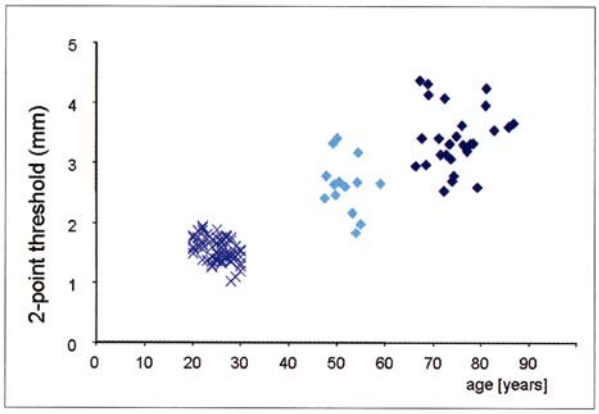

FIGURE 3.
Tactile two-point discrimination thresholds of the tip of the right index finger as a function of age (total of 120 subjects). Note almost linear decline over lifespan. Modified and reprinted with permission from Annals of Neurology *[7].*

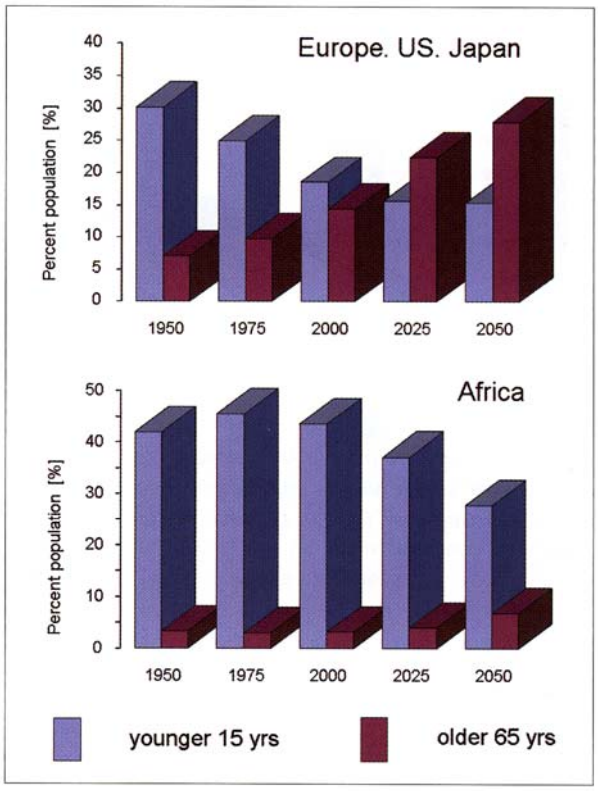

FIGURE 4.
Development of the ageing structure of the industrialised countries US, Europe and Japan, and for comparison from countries of Africa. Adopted from: World Population Prospects. The 2002 Revision. *UN, New York.*

acceleration exerted to the skin. The resulting information is coded into action potentials and transmitted to the brain for further processing in order to create conscious perception about texture properties.

A general scheme is that the distribution of the various receptor types is not uniform across the body, but high in those skin portions that are particularly sensitive, such as finger tips or lips. In addition, receptor distribution varies dramatically inter-individually making tactile and haptic sensation highly variable across a human population.

Among factors that have a major impact on tactile and haptic sensation is age. There is a tremendous age-related decline of performance over age, which starts already at an age of 30 to 35 and then almost linearly continuous to decline over the rest of the lifespan [5–7]. Figure 3 depicts an example of how tactile acuity, the ability to tell two closely spaced points in space apart, is worsening over age. Age-related deterioration of tactile and haptic sensation is not only critical from an individual point of view, but also from a socio-political view: We witness a unique restructuring of the ageing pattern in the societies of the industrial nations, characterised by an increasing probability to reach old age (Fig. 4). As a result, the constraints of everyday-living differ for a huge proportion of the population from that of the younger counterpart. In the context of designing haptic structures, ageing constitutes an important factor that has to be taken into account.

Besides ageing, factors such as deliberate practice, experience and use greatly influence haptic perception. Haptic performance of the fingers is significantly enhanced in subjects who are using their fingers much above average. Typical

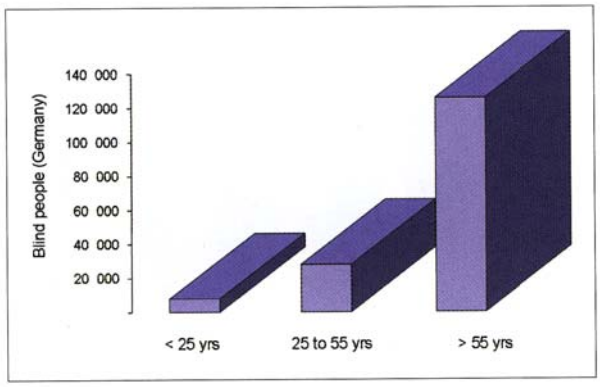

FIGURE 5.
Ageing structure of people in Germany suffering from blindness or severe vision impairment. Federal Statistical Office, Germany (2003). German Association of the Blind.

examples are musicians and those that are blind. Particularly, blind subjects who read Braille with their fingers develop an extraordinary level of tactile performance which is maintained into high age [8–10].

In Germany, about 0.05% of the total population suffers from blindness or severe vision impairments (Fig. 5). Despite the relatively small percentage, some countries have included Braille characters or specifically designed raised dot patterns to support blind people in recognising banknotes. For example, Lederman and Hamilton reported about the specific design of dot patterns that were tested and later incorporated into new banknotes issued by the Bank of Canada [11].

Constraints for banknote design

For the design of haptic features of banknotes, two aspects are important:

First, given the substantial technical possibilities to produce almost any types of extremely fine-grained intaglio structures, it is not clear, which tactile features are particularly suited to create strong haptic sensations in human users, and thus are optimal for being utilised in banknote authentication.

Second, in the context of haptic design and optimisation of tactile features for banknotes, a number of constraints have to be met which arise (arranged in the order of priority) from a number of factors that might not necessarily match those required for haptic authentication:

- politics
- technical (printing and paper quality)
- graphics and aesthetics
- tactility and haptics
- human factors

To consider human factors adequately, the following constraints have to be taken into account:

- A normal distribution of tactile and haptic performance in a 'idealised' population
- The effect of ageing, in particularly different age-groups
- the existence of specialised subgroups, such as blind individuals

Haptic banknote design: effective intaglio structures and their reliable recognition throughout the population

The following describes results from a study in cooperation with Giesecke & Devrient GmbH, Germany [12], in which tactile and haptic properties of banknote-like intaglio printing was investigated in three right-handed subgroups consisting of young adult subjects (aged 21–29 years), middle-aged to elderly subjects (aged 52–68 years), and middle-aged to elderly blind subjects who acquired blindness late in life and who were proficient Braille readers (aged 53–65 years).

Psychophysical tests

The task consisted of comparing in a two-alternative forced choice paradigm pairs of intaglio

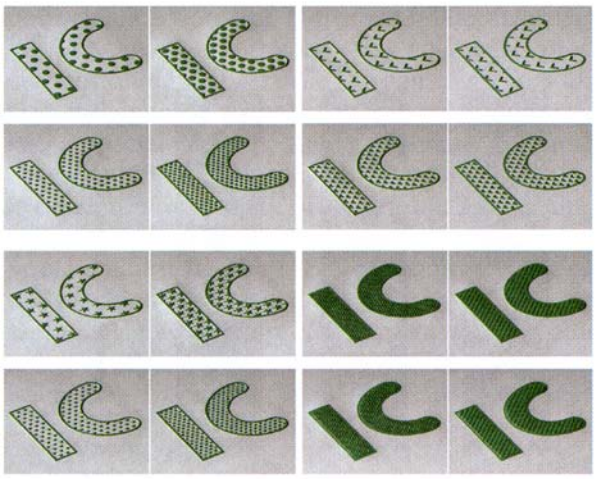

FIGURE 6.
Examples of the intaglio structures and value numerals used in the present investigation. Form elements used to fill the numerals were stars, dots, open triangles and line patterns that varied in size and spacing.

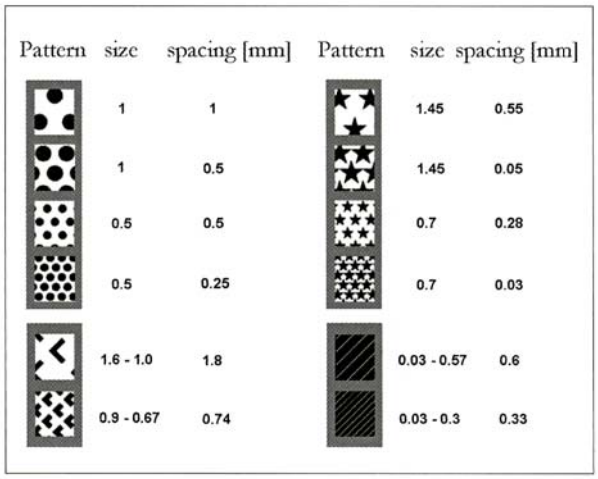

FIGURE 7.
Schematic illustration of the form elements and their dimensions (values given in millimetres).

structures on banknote-like sheets, which were printed on banknote-paper (105×50 mm); for illustrations of different specimens used see Figure 6. The papers contained intaglio pattern of different form elements of varying size and spacing embedded in two value numerals (width 3 mm, height 13 mm, separation 2 mm) approximately covering an area of 13×13 mm in size. According to optical interference measurement relief height was between 85 and 95 microns. For a schematic overview of the form elements tested see Figure 7. In addition, the value numerals could either have an outline with the same relief height as the form elements, or without an outline. Subjects were asked without sight to explore the value numeral with their thumb or index fingers and report whether pairs of notes were the same or different. To obtain information about the affective aspects of the pattern tested, subjects were also asked to rate each specimen according to pleasantness on a scale from 1 to 4 with 1 "very unpleasant" to 4 "very pleasant". Each pattern was compared to each other in one session (300 comparisons), once with the index finger and once with the thumb, according to discriminative and to affective properties. Each session was repeated eight times resulting to a total of more than 6,000 comparisons in each subject.

Discrimination/identification performance

Similarity rating depended on form, size, spacing and outlining. No general trend could be found accept that patterns made up from linings performed best. In Figure 8 the top 30th percentile of the pattern that yielded best and worst identification (correct rating) are shown. Among those performing best, all patterns investigated were represented except for open triangles, which performed worst. Outlining was found in most of the worst performing pattern indicating that this feature seems to prevent correct identification. No significant differences were observed for conditions when subjects used either the index finger or the thumb for exploration.

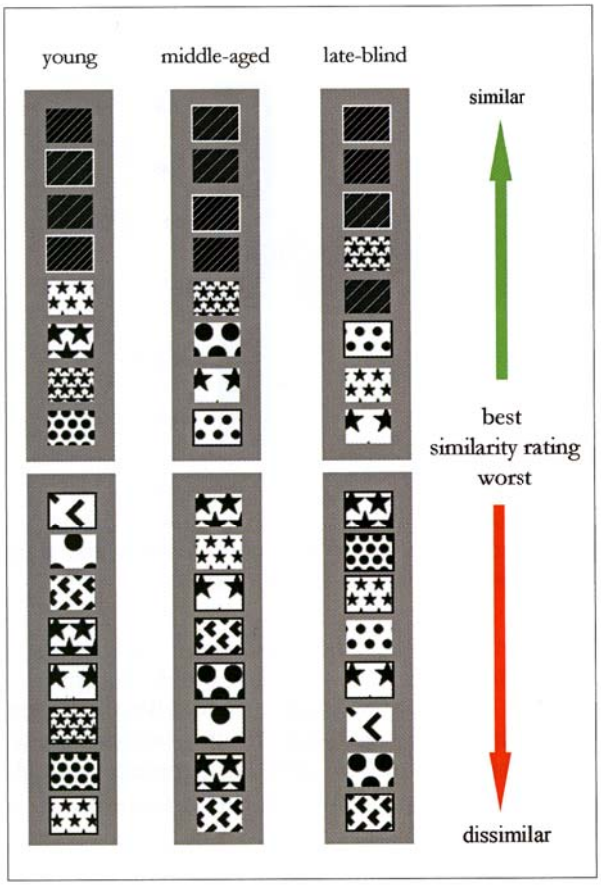

FIGURE 8.
Example of pattern of the 30th percentile yielding best (top) and worst (bottom) similarity rating. Shown are data for all subgroups tested: young adults (left), elderly (middle), and elderly, late blind people (right).

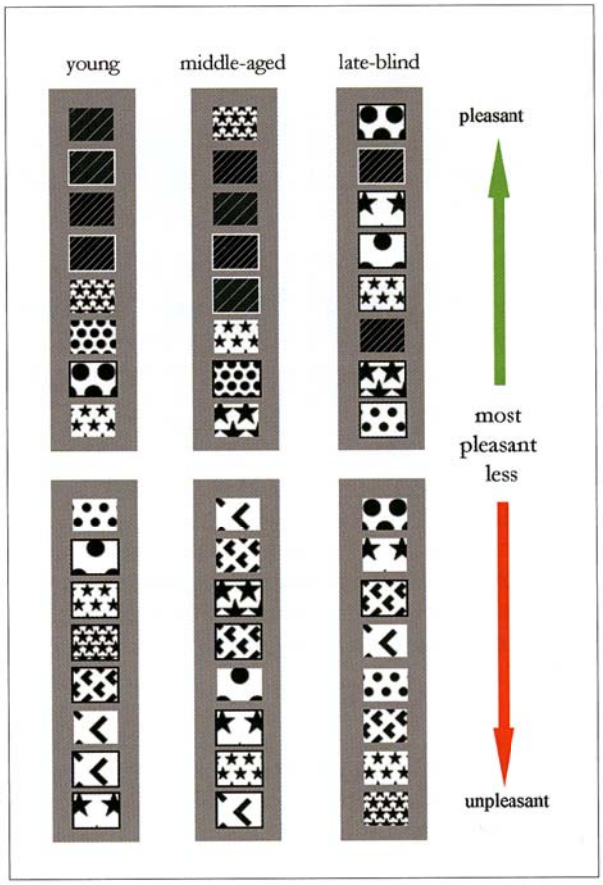

FIGURE 9.
Example of pattern of the 30th percentile yielding highest (top) and lowest (bottom) pleasantness rating. Shown are data for all subgroups tested: young adults (left), elderly (middle), and elderly, late blind people (right).

Affective performance

Subjects successfully rated patterns according to 'pleasant' and 'unpleasant'. In Figure 9 the top 30th percentile of the pattern that yielded highest or lowest pleasantness rating are shown. Again, there seemed to be no general trend. Surprisingly, there was a considerable match concerning pattern that yielded high similarity rating and those that yielded high pleasantness rating. Accordingly, a subgroup of patterns is similarly suited to provide effective discriminative as well as affective performance.

Dependence on pattern (form, size, spacing, outlining)

As noted above, there was no general trend in the sense that certain form elements, dimensions or spacing showed systematic superiority above others. The only form elements that yielded best

performance were line patterns of different spacing. For the other form elements no general preference could be observed. The same was true for size and spacing of the form elements. Outlining had a crucial effect on the performance. In most cases, outlining impaired identification (outlining is present in only eight out of 24 pattern yielding high similarity rating, but in 16 out of 24 yielding poor similarity rating). For pleasantness rating the situation is slightly different, as young adults and elderly subjects prefer pattern without outlining, while in blind subjects the opposite was found (Fig. 9).

Local *versus* global features

Roughness is a conventional measurement of small-scale variations in the height of a physical surface. Usually, spacing, size and density of raised elements are crucial factors that determine texture perception. In the patterns studied here, four different components play a role in creating the perception of roughness and texture:

1. components resulting from the single form elements (i.e., edges in case of stars, smooth curves in case of dots, etc.)
2. components resulting from the spacing and size of the single form elements
3. components resulting from the outlining
4. components resulting from the overall size of the value numeral, which limits the number of form elements within

A recent multidimensional analysis of texture of raised-dot patterns revealed that three orthogonal perceptual dimensions can account for the judged tactile dissimilarities: blur, roughness, and clarity [13]. These authors also reported that dot-pattern roughness and individual-dot roughness corresponding to roughness produced by the single form elements and roughness produced by the spacing and size of the form elements affected perceived roughness differently.

The contributions of the single form elements were denoted as local, and those of the spacing

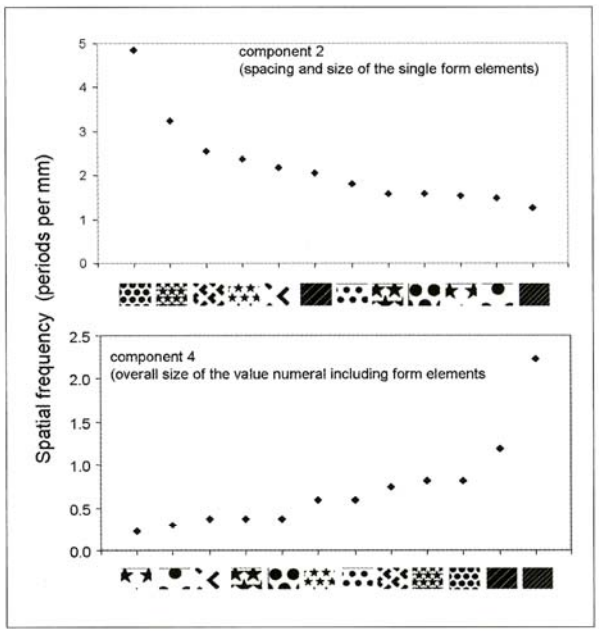

FIGURE 10.
Spatial frequencies as calculated by means of a spatially two-dimensional Fourier analysis for component 2 (spacing and size of the single form elements) and component 4 (overall size of the value numeral including form elements). According to this analysis, the different components cover different frequency ranges with only a slight overlap.

and size as global. In order to illustrate the different texture properties evoked by the above mentioned components, the spatial frequencies were calculated by means of a spatially two-dimensional Fourier analysis for component 2 (spacing and size of the single form elements) and 4 (overall size of the value numeral including form elements). Figure 10 illustrates the spatial frequencies for all pattern combinations. This analysis demonstrated that the different components cover different frequency ranges with only a slight overlap. In addition, as depicted in Figure 10, the different components result in different similarities between patterns, which is one of the reasons for the poor predictability of pattern performance.

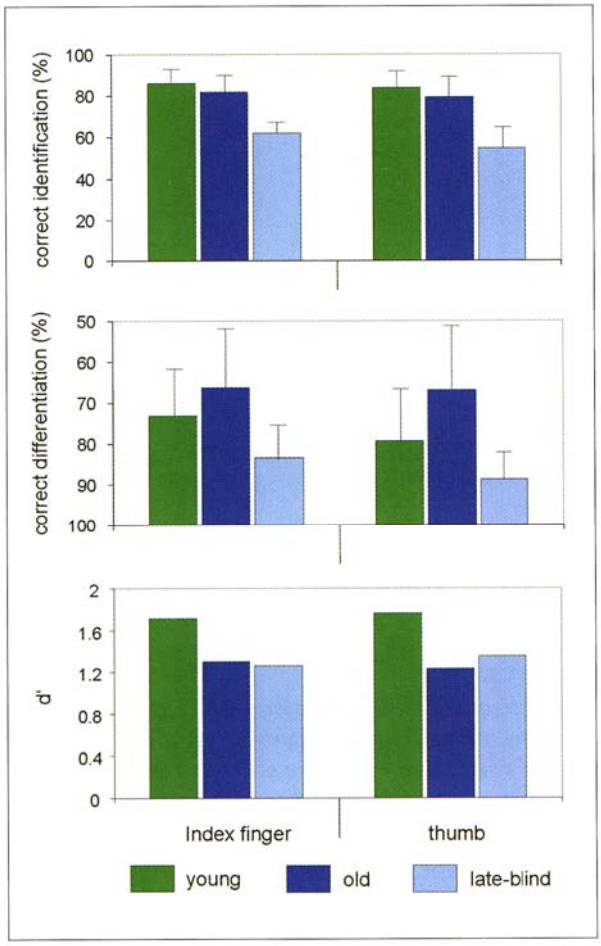

FIGURE 11.
Average performance scores for all three subgroups tested. a) similarity rating (% correct identification, 100% up) based on comparisons of 24 identical pattern. b) dissimilarity rating (% correct differentiation, 100% down) based on comparisons of 276 non-identical patterns. c) Overall detection performance (d-prime).

Comparison across subgroups: young adults – elderly – blind

Without exception, all participants were able to succeed the different tests. Figure 11 summarises the average performance measured across all subjects in all subgroups. To obtain a quantitative measure of correct performance, the so-called d-prime (or d') was calculated as a sensitivity index usually used in signal detection theory. An estimate of d' is obtained from measurements of the hit rate and false-alarm rate. A higher d' indicates that the signal can be more readily detected.

As expected, the group of elderly adults showed the poorest performance. Besides this observation, which is consistent with the age-related decline of tactile abilities, this group showed another characteristic feature in the pleasantness rating. It was found that the dynamic range was much smaller, presumably because elderly subjects were hesitant to assign extreme scores.

Surprisingly, the group of late blinds did not outperform the remaining participants, but showed a comparable performance as the age-matched sighted subjects (Fig. 11c). To understand this result, the performance obtained for identical and different pattern was more closely analysed. As can be seen in Figure 11b, blinds yielded best performance in a task of telling two different patterns apart. However, in a task consisting of identifying two prototypes with the same pattern, their performance dropped below that observed in the other groups. Questioning the participants after the end of the testing revealed an interesting feature: Blind subjects were able to detect even tiny differences of the prototypes. When two identical patterns had to be identified as 'same', because they were on physically different prototypes blinds were able to sense small differences in paper texture and surface properties, which led them more often report 'different' although the pattern were 'same', which resulted in an overall poor identification performance and thus in a high false alarm rate, which caused a small d' (Figs 11b and c). This outstanding ability explains their poor performance in this task, but highlights at the same time their unusual tactile abilities confirming other reports.

Comparing the outcome of the three subgroups revealed another important finding: While

there were clear quantitative differences between subject groups, their overall performance was qualitatively comparable. As illustrated in Figure 8, the three subgroups shared five out of eight patterns that yielded best rating (young *versus* elderly: 5 of 8, young *versus* blind: 6 of 8, elderly *versus* blind: 7 of 8). For pleasantness rating a similar outcome was observed for young *versus* elderly (6 out of 8), while blind subjects showed a different preference (young *versus* blind: 3 of 8, elderly *versus* blind: 2 of 8). These findings demonstrate that despite the differences in absolute rating scores observed in the three subgroups, their preferred patterns share many similarities, both in terms of discriminative and affective performance. For making decisions about banknote design this feature is of particular implication as it facilitates haptic design by matching tactile sensing constrains found across different populations.

Non-predictability of pattern effectiveness: role of context

An unexpected finding was the poor predictability of pattern effectiveness. Decades of research on tactile texture and surface properties have revealed insight into crucial parameters determining texture and roughness perception. So one might have expected that pattern effectiveness can be more easily predicted from what is known about tactile texture and roughness perception. According to an elaborate study on texture discrimination abilities in humans, subjects seem to use spatial rather than intensive cues when discriminating patterns of similar density, suggesting that the similarity of form, i.e., the spatial arrangement of the closely spaced dots is more readily apparent than small differences in spacing along the axis of motion [14]. Besides spatial and intensity cues there is a discussion about the role of temporal cues such as the speed of scanning a texture with the finger, which corresponds to temporal frequency [15]. Remarkably, subjects appeared to be most successful in differentiating texture patterns when they were able to mentally picture the orientation and spacing of the pattern [14].

According to the experimental findings reported here, outlining is a very unpredictable source of disturbance and interference of tactile perception. In studies of tactile perception, interferences of this type have been intensively studied in the context of attempts to convey information to the skin by means of vibratory patterns such as letters of the alphabet [16]. For example, localisation of a tactile stimulus was affected by the temporal separation between the target and a tactile masker suggesting a role for temporal interferences [17]. In the visual domain, substantial modulation of target processing by introducing spatial context is well documented [18].

Another reason that outlining has such a severe modulatory effect comes from the fact that the form elements were confined to a small area within the value numeral. Dependent on the size and spacing of the form elements along the horizontal axis of the value numeral only one or two elements could be accommodated which increases the impact of the outlining in comparison to that of the form elements. As a consequence, designs of effective intaglio structures have to be individually tested and optimised in each case dependent on the overall graphical and other requirements.

Summary

Progress in printing technologies has made it possible to create intaglio structures of enormous spatial details. During the recent years, tactility and haptic features generated by intaglio structures are more and more used as additional security features to impede counterfeiting. Due to the strong visuotactile coupling the vision-touch combination offers unique advantages for spontaneous and almost unconscious banknote authentication of the end user. However, there is no *a priori* knowledge about which tactile features are particularly suited to create strong hap-

tic sensations, and thus are optimal for banknote authentication. This is true because many human factors have to be considered such as the normal distribution of tactile and haptic performance in an 'idealised' population, the effect of ageing, because age deteriorates tactile perception, and the existence of specialised subgroups, such as blind subjects characterised by superior tactile abilities.

Psychophysical assessment of several form elements typically used in banknote design embedded in value numerals were tested according to their discriminative and affective properties in three groups of young adults, elderly subjects and age-matched late-blind people with profound Braille reading abilities. Size and spacing of the form elements were varied, and value numerals were presented with and without an outline. While there were clear quantitative differences of performance between groups, their overall performance was qualitatively comparable. These findings show that despite the differences in absolute performance observed in the three subgroups, their preferred patterns shared many similarities, both in terms of discriminative and affective properties. A number of patterns appear to match the different tactile sensing constrains found across different populations. This finding bears considerable implications for haptic banknote design.

One might have expected that pattern effectiveness can be more easily predicted from what is known from the literature about tactile perception. According to the data presented here this is not the case, as massive contextual factors such as an outline modulate perception making overall performance highly unpredictable. In addition, local (such as single form elements) and global features (such as the arrangement of form elements in terms of periodicity and density) contribute differentially to the overall tactile perception, i.e., the single form elements and the patterns created by assembling them through adjustment of size and spacing have different perceptual properties. As a consequence, the design of effective intaglio structures has to be individually tested and optimised in each case dependent on the overall graphical and other requirements.

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Important websites

Banknote2006. The definite forum on emerging trends and leading technologies in the banknote industry. http://www.banknote2005.com/banknote_home.html

Deutsche Bundesbank – Eurosystem: http://www.bundesbank.de/index.en.php

Giesecke and Devrient GmbH: http://www.gi-de.com/

Haptec Research and Technology GmbH: http://www.haptec.de

Haptics-L: The electronic mailing list for the international haptics community: http://www.roblesdelatorre.com/gabriel/hapticsl/

The Bureau of Engraving and Printing – United States Department of the Treasury: http://www.moneyfactory.gov/

The Haptics Community Web Site:
http://haptic.mech.northwestern.edu/
The Perceptual Learning mailing list:
http://cogmod.osu.edu/mailman/listinfo/plearn
The wiki of the international community of scholars studying perceptual learning:
http://www.perceptuallearning.org/
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