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Stimulus duration thresholds for reading numerical time information: Effects of visual size and number of time units

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ABSTRACT

We examined the effects of the visual size and the number of digits on reading numerical time information in young adults. Using an adaptive staircase procedure, minimal stimulus presentation duration (MSPD) for 80%-correct responses was determined for visual sizes ranging from 0.1° to 15°, when reading 1 ("mm"), 2 ("hh:mm") or 3 ("hh:mm:ss") 2-digit units of time information. All three time types revealed U-shaped relations between MSPD and visual size, with the characteristics of the relation depending on the number of time units. Time type had two different effects. First, longer time types gave rise to longer MSPDs, as more elements needed to be encoded into working memory. Second, longer time types gave rise to smaller ranges of optimal visual character size, decreasing from 0.2–2° for the 1-unit time type to 0.3–0.5° for the 3-unit time type. The lower boundary of the optimal range of visual size may be understood as resulting from acuity limitations. The shift in the upper boundary of the optimal range of visual size is suggested to reflect the change in size of the visual span associated with larger visual character sizes.

1. Introduction

A consequence of the increasing presence in daily life of electronic accessories with visual displays is that we are more and more confronted with numerical information. While numbers may of course be represented in word form by verbal numerals (e.g., "seven" or "twenty-four"), representation in digit form by Arabic numerals (e.g., "7" or "24") allows a much more efficient use of presentation space. Numerical time information, for instance, is typically presented by two-digit groups of Arabic numerals, separated by colons.

Although digit-form numerical information is extensively used in displays, number legibility has not received the same amount of experimental attention as text legibility. As a result, visual ergonomics has either implicitly assimilated numbers to letters (or words) or has simply ignored them. Interestingly in this regard, the European standard of requirements for electronic visual displays [15] defines minimal, maximal, and preferable visual sizes for text characters, but not for number characters. Yet, important neuroanatomical and functional differences have been demonstrated between number reading and text reading [3,4,10,11,12,25,33,40,43,47].

Low-level visual processes underlying the identification of individual digits may be expected to be similar to those underlying the identification of individual letters, but multi-digit numbers cannot be assimilated with multi-letter words: The latter are characterized by recognizable global patterns that allow individual characters to be ignored (cf., [5,39,44,46,49]) while the former are not. Moreover, while numbers can be formed by any combination of digits, certain combinations of letters form words while others do not. Using an established psychophysical method, in the present contribution we examined the effects of the visual size and the number of digits on reading numerically represented time information.

Under normal contrast and luminance conditions, the speed of text reading is maximal when the letter characters subtend visual angles between 0.3° and 2° [7,22]. Below 0.3° of visual angle text reading speed decreases (also see [16,24] for electronic devices), most likely due to limitations in visual acuity. Beyond 2° of visual angle text reading speed also decreases, indicating that the use of larger characters is not necessarily beneficial [22]; also see [50]. This latter effect has been attributed to decreasing letter acuity in peripheral vision, crowding between adjacent characters, and decreasing accuracy of position signals in peripheral vision [18]. These mechanisms can give rise to an increase in the number of fixations, separated by the saccadic eye movements that characterize text reading [41,46]. Because the effect of character size in text reading is thus mainly explained by low-level visual

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processing characteristics, one may expect similar effects of character size in number reading. Our working hypothesis was thus that number reading would reveal an optimal size interval that lies in the same range (0.3–2° of visual angle) as that identified for text reading.

Word length is known to influence reading speed [19], with longer words evoking longer fixation durations [14,27], presumably due to the increase in the quantity and complexity of information that needs to be processed [38]. Longer numbers (i.e., numbers with more digits) also require a longer processing time [11,32], which is known as the magnitude effect [3]. Yet, processing of Arabic numbers is quite different from processing verbal material [3,26,40,43] and therefore the reasons underlying the word-length effect cannot be directly transposed to the magnitude effect. Moreover, rather than giving rise to longer numbers, increasing the precision of numerical time information typically leads to series-extensions of two-digit numbers, representing for instance hours (hh), minutes (mm), and seconds (ss). While it remains unclear whether two-digit numbers are processed separately or as an ensemble [3,25,28,35], reading numerical time involves processing of a series of two-digit numbers. Based on the effects of the number of units to be processed on processing duration (e.g., [45]), an increase in the number of two-digit numbers is expected to lead to an increase in the required reading time.

In the present study we determined the minimal visual presentation duration required to accurately read numerical time information. Using a psychophysical staircasing procedure [17], we explored the effects of character size and number of two-digit information units.

2. Material and methods

2.1. Participants

Twelve young adults (6 men and 6 women, age 21 ± 5 years) participated in the study. All had a corrected or uncorrected visual acuity of at least 10/10 for each eye, as determined by a 5-m Monoyer test. Participants provided written consent prior to the study, which was conducted according to University regulations and the Declaration of Helsinki.

2.2. Apparatus and stimuli

Stimuli were presented in the center of a 22-inch LCD screen (Samsung SyncMaster 2233 RZ, 1680 × 1050 pixel resolution, 32-bit color coding) operating at 100 Hz. Synchronization with the 10-ms refreshment cycle of the screen was controlled by E-Prime® 2.0 software (Psychology Software Tools, Inc., USA), running on a HP Z400 Workstation (Intel® Xeon® CPU W3520 @ 2.67 GHz 1.57 GHz, 3 Go RAM, NVIDIA Quadro FX 1800 graphic card, Microsoft Windows XP Professional SP3 OS). Viewing distance was controlled using a frontal headrest that also ensured alignment of the participant's eyes with the center of the screen.

Stimuli consisted of combinations of one, two, or three two-digit groups, representing time information in a numerical format ("mm", "hh:mm" or "hh:mm:ss" with $00 \leqslant hh < 24$; $00 \leqslant mm < 60$; $00 \leqslant ss < 60$). Each stimulus presentation was immediately followed by a 500-ms mask of the appropriate dimension ("$$", "$$:$$", "$$:$$:$$"). Characters were presented in the Digiface font (see Fig. 1), a constant-width font comparable to the 7-segment fonts used in classical LCD displays. They were presented in mesopic viewing conditions, in black against a white 110 cd/m^2-luminance background with a mean Michelson contrast of 85%.

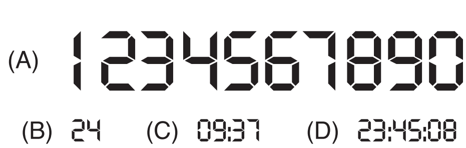

Fig. 1. Numerical characters of the Digiface font (A) and examples of stimuli in the "mm" (B), "hh:mm" (C), and "hh:mm:ss" (D) time type formats.

2.3. Task and procedure

The duration of stimulus presentation varied sequentially over trials following an adaptive staircase procedure. On each trial, a fixation cross was presented in the center of the screen during 2 s, followed by a stimulus (presented for a duration depending on the staircase procedure) and the 500-ms mask. Before the start of the experimental phase, participants were familiarized with the visual task during a one-minute training session with fixed and sufficiently long presentation durations.

During the experimental phase, after each stimulus presentation participants had to enter the perceived sequence of numbers on a keyboard placed on the table in front of them before the next trial started. Stimulus presentation duration was adapted during the sequence using an adaptive three-down/one-up staircase, leading to the threshold for 80% correct responses [17]. Starting from a sufficiently long initial stimulus duration, this duration was decreased in time steps of 40 ms following each series of three consecutive correct responses. When an error occurred, duration was increased by 40 ms. After the first four inversions, the time step was reduced to 20 ms. After the next three inversions, the time step was further reduced to 10 ms. The procedure ended after 12 inversions. The perceptual threshold (corresponding to the presentation duration for 80% correct responses) was calculated as the mean of the last four inversion values.

Perceptual thresholds were obtained for each of the three time types (formats "mm", "hh:mm", and "hh:mm:ss", corresponding to one, two, or three two-digit groups) at each of nine different sizes (0.1°, 0.2°, 0.3°, 0.5°, 1.0°, 2.0°, 5.0°, 10.0°, and 15.0° visual angle).

To this end, participants performed a total of 9 blocks of trials – three for each time type – with each block presenting three interlaced staircase procedures for the same time type ([0.1°, 0.2°, 0.3°] or [0.5°, 1.0°, 2.0°] or [5.0°, 10.0°, 15.0°]). Blocks were presented in randomized order and lasted about 12 min per block. Participants rested for a minimum of 15 min between blocks.

The size and resolution of the screen used in the present experiment did not allow to correctly present stimulus for each visual size at a single viewing distance. Nevertheless, all tests were performed in binocular close viewing: 15 cm for the 5.0°–10.0°–15.0° blocks and 65 cm for the other blocks. Each participant completed the full experimental session on a single day in order to minimize within-participant variability.

2.4. Statistical analysis

After verification of the normality of the data distribution with Lilliefors and Shapiro–Wilk tests, effects of Time Type and visual size on the perceptual thresholds were assessed using a two-way repeated-measures Analysis of Variance (ANOVA). Effect sizes were determined using partial η^2. Differences between conditions were further explored using Tukey HSD post hoc tests.

3. Results

The ANOVA revealed significant main effects of both Time Type ($F(2, 22) = 338.6$, $p < .001$, $\eta^2{}_p = .97$) and visual size ($F(8, 88) = 122.3$, $p < .001$, $\eta^2{}_p = .92$), as well as a significant Time Type ×