The syllable-length effect in number processing is task-dependent

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Two experiments were run in order to investigate the relationship between syllable length of number names and eye-fixation durations during silent reading of one- and two-digit numbers. In Experiment 1, subjects had to read a series of three numbers and recall them orally; in Experiment 2, subjects had to indicate manually whether the value of the middle number was between the values of the outer numbers. The effect of syllable length was controlled for possible confounding effects of number frequency and number magnitude. Findings indicated that fixation duration depended on syllable length of number names in the first task, but not in the second task. The results call into question the claim that phonological encoding is imperative in visual processing; phonological encoding was used only when the numbers had to be recalled, and not when they were coded for computational purposes.

Pynte (1974) showed that the relationship between syllable length of number names and response latency previously found for number naming (Eriksen, Pollack, & Montague, 1970; Klapp, 1971, 1974) also existed in silent number reading. Two series of three two-digit numbers were each presented for 2 sec. Subjects had to read the numbers silently and to report them aloud as soon as the stimulus display disappeared. Eye movements were tracked while the subjects were reading. Pynte (1974) found that gaze duration on the center number increased as the syllable length of the number name increased, although pronunciation was not required during processing. This led Pynte to the conclusion "that a mechanism of readiness for pronunciation co-occurs with visual processing" (p. 110).

Pynte's (1974) finding is regularly cited, along with other studies, as evidence that phonological encoding is an essential element in visual processing (see, e.g., Hung & Tzeng, 1981; Rayner & Pollatsek, 1989, p. 214; Rossi, 1985). However, before Pynte's (1974) results can be used as unequivocal support for phonological mediation in reading, alternative interpretations must be ruled out. Pynte used only two times two critical stimuli: "30" (*trente*, one syllable) versus "90" (*quatre-vingt-dix*, four syllables), and "28" (*vingt-huit*, two syllables) versus "82" (*quatre-vingt-deux*, four syllables). This leaves open the possibility that the findings were due to factors other than syllable length of the stimulus name. First, Pynte did not consider the frequency of occurrence of his stimuli, so that his results may have been an artifact of the large num-

bers' having lower frequencies than the low numbers. Second, it is not unreasonable to assume that large numbers are more difficult to process than small numbers, so that Pynte's syllable effect might also have been due to differences in number magnitude. Finally, it can be asked whether Pynte really did design a task "without pronunciation." Though naming was not required during reading, the subsequent oral report of numbers may have entailed subvocalization as part of response preparation.

To address the three criticisms above, we ran two replications of Pynte (1974), in which all of the important factors were controlled: In Experiment 1, a number recall task similar to Pynte's was used. In Experiment 2, subjects had to compare numbers without vocal report. The weight of each critical factor (syllable length, number frequency, and number magnitude) was assessed with multiple regression analyses on the eye-fixation data.

EXPERIMENT 1

To investigate whether Pynte's (1974) syllable-length effect remained valid if number frequency and number magnitude were partialled out, the paradigm was repeated for all numbers smaller than 100, instead of the original pairs 30-90 and 28-82. Because there were no objective measurements of number frequency available, subjective estimates were used (see Method).

Method

Subjects. Eleven native Dutch-speaking undergraduate psychology students from the University of Leuven participated in the experiment. None of the subjects wore glasses or lenses. All were unaware of the purpose of the study. The data of 2 additional subjects were excluded on line because of unsatisfactory eye-movement registrations (see the section on dependent variables).

Stimuli. The stimulus display of each trial consisted of three numbers, presented on the left, center, and right of a CRT screen (see Figure 1). One hundred trials of three random numbers were

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Figure 1. Stimulus display.

presented to all subjects. Numbers and trials were randomized, with the following constraints: (1) All numbers from 0 to 99 appeared once as the left, middle, and right numbers, and (2) all three numbers in each display were either single-digit or double-digit numbers. Each subject received a different set of stimuli (for more information, see Brysbaert, 1991). The subjects sat 70 cm in front of an ETAP screen, a large CRT screen that subtends 36 cm horizontally (i.e., 27° at a distance of 70 cm) and 26 cm vertically. It made use of the fast-decaying P4 phosphor. The three numbers of a trial were separated from one another by a visual angle of 8° , in order to exclude parafoveal preprocessing. Digits were $.57^\circ$ high and $.48^\circ$ wide.

Task. The subjects were instructed to look at the fixation point (colon) on the left side of the screen (see Figure 1) until a trial was presented. Adequate fixation was ensured with the eye-movement system (see below). As soon as the numbers appeared, the subjects had to read them silently from left to right. The stimuli were presented for 2 sec, after which the subjects repeated them aloud. The experimenter recorded the subjects' accuracy on the center number. Trials in which eye-movement registration was deficient were repeated at a random place later in the series. This occurred on 14 out of a total of 1,100 trials.

Independent variables. Because all numbers from 0 to 99 were used, number magnitude ranged from 0 to 99 and syllable length of number names (in Dutch) from 1 to 6. Number frequency was assessed with a questionnaire. Twenty students, from the same population as the subjects in the experiment, rated the numbers on a scale ranging from 1 (*extremely rare*) to 6 (*extremely frequent*) with respect to frequency in everyday life. Afterward, the answers were linearly rescaled (by subtracting 1 and multiplying the result by 100) in order to get a frequency range between 0 and 500. In this way, integer numbers were obtained without their being rounded off. Previous research with words had indicated that such subjective estimates of frequency are both reliable (Galbraith & Underwood, 1973; Shapiro, 1969) and highly correlated with objective and tabulated measurements (Gernsbacher, 1984). The values of the three independent variables for all numbers are listed in the Appendix.

Dependent variables. Eye movements were registered with Debic-80 equipment on the basis of pupil-center corneal reflection (Young & Sheena, 1975), with a sampling rate of 50 Hz. The system was accurate to 0.5° and was interfaced with a PDP-11/40 computer that kept a complete record of the x and y coordinates of the subject's point of regard. During the measurement, the experimenter could follow the point of regard on a monitor, in order to check whether the subjects looked at the fixation point before the stimuli appeared and whether the eye-movement registration was satisfactory. Raw data were transformed to fixations by means of a data reduction program (based on Kliegl & Olson, 1981). A fixation was defined as a sequence of at least five consecutive measurements (i.e., 100 msec) whose x and y coordinates did not deviate more than 1° horizontally and 0.75° vertically. Because estimates of fixation durations based on reduction programs outlined above are sensitive to missing values, an analysis of the percentage of missing values was performed. The percentage amounted to 1.5% and was not correlated with any of the independent variables (correlations were smaller than $+.10$ and $-.10$).

Only fixations on the center number were analyzed. A distinction was made between first-fixation duration (FFD) and first-gaze duration (FGD). FFD is the duration of the very first fixation on the center number. FGD is the sum of FFD and all consecutive fixations the first time the center number is looked at (i.e., without regressive gazes). The distinction between FFD and FGD is commonly made in eye-movement research (De Graef, Christiaens, & d'Ydewalle, 1990; Inhoff, 1984; Rayner & Pollatsek, 1987), because it is believed that FFD reflects initial processing, whereas FGD also includes relatively late cognitive processing. Thus the distinction can give some information about whether phonological information is accessed during encoding (FFD) and/or during further processing (FGD).

Procedure. Each subject was tested individually, after an explanation of the experimental setting and task. The subject sat in an adjustable chair 70 cm in front of a CRT screen. The chair could be adjusted for height and position of the headrest. In addition, a chinrest was used to prevent small head movements. Before the 100 test trials were administered, the eye-movement registration system was calibrated and 10 practice trials with letters instead of numbers were presented to ensure that the subject understood the instructions correctly. After the test, subjects received feedback about their performance. The whole experimental session took about 35 min.

Results

The three predictor variables—syllable length, number frequency, and number magnitude—were highly inter-correlated. Pearson correlation coefficients amounted to $-.753$ ($n = 100$, $p < .01$) between syllable length and number frequency; $.718$ ($n = 100$, $p < .01$) between syllable length and number magnitude; and $-.621$ ($n = 100$, $p < .01$) between number frequency and number magnitude. The substantial negative correlation between syllable length and number frequency is interesting because it is in line with word findings (cf. the so-called Zipf law; Zipf, 1935, 1949). At the same time, the high correlations between the predictor variables support our criticisms of Pynte's (1974) results.

The subjects' error rate was 4.7%. Analysis of the eye-fixation data revealed no significant difference between correct and incorrect trials. Therefore, the remaining analyses are based on all trials.¹ In addition, 13 missing cells (i.e., 1.2%) had to be estimated with the procedure from Yates (1933), which enables one to calculate missing observations from the sum of the subject's other observations and the sum of the remaining observations for the stimulus in question (see also Kirk, 1982, pp. 268-270). Mean FFD of the results thus obtained amounted to 266 msec; mean FGD was 404 msec. Mean FFD and FGD per number are presented in the Appendix.

Correlations between the predictor variables and the eye-fixation data are listed in Table 1.² The first line for each dependent variable, FFD and FGD, gives the raw Pearson correlation coefficients; the second line shows the correlations when the effects of the two other variables are partialled out; the third line, finally, lists the results of a model that will be explained below. Syllable length correlated significantly with both FFD and FGD, even when the effects of number frequency and number magnitude were partialled out. This means that Pynte (1974)

Table 1
Raw Correlations, Highest Order Partial Correlations, and Partial Correlations
According to the Model for First-Fixation Duration and First-Gaze Duration
in the Number-Recall Task (Experiment 1)

	Syllable Length	Number Frequency	Number Magnitude
First-Fixation Duration			
Raw correlation	.401*	-.366*	.181
Highest order partial correlation	.270*	-.140	-.191
Partial correlations model†	.401*	-.106	-.191
Final model: FFD = 217.24 + 13.11 Syl			
First-Gaze Duration			
Raw correlation	.678*	-.667*	.506*
Highest order partial correlation	.326*	-.322*	-.020
Partial correlations model†	.678*	-.323*	-.020
Final model: FGD = 399.62 + 25.30 Syl - 0.36 Freq			

Note—FFD = first-fixation duration. Syl = syllable length. FGD = first-gaze duration. Freq = number frequency. Mag = number magnitude. * $p < .01$, two-tailed. †Model: 1 = Syl, 2 = Freq, 3 = Mag.

has been successfully replicated. Number frequency was also correlated with FFD and FGD, and number magnitude was correlated with FGD (see Table 1); but only the correlation between number frequency and FGD remained significant when the effect of the other variables was partialled out.

Raw correlations inflate the importance of predictor variables if these variables are interrelated. Highest order partial correlations, on the other hand, underestimate the true weights, because the effect of each variable is partialled out for possible effects of all other variables. Therefore, a model was developed in which the variables were entered successively. In this way, correlations were only partialled out for effects of previously entered factors. To develop such a model, it is customary to enter the variables with the largest correlations first. However, because the differences between the correlations for syllable length and number frequency were only marginal, it was not evident which of the two predictors dominated.

Therefore, we ran an analysis of variance (ANOVA) on a subset of 16 two-digit numbers for which the predictor variables were independent. A $2 \times 2 \times 2$ design was obtained by taking high and low values for each variable. Each cell contained two numbers with an average value 1.5 SDs above or below the mean. These numbers are indicated in the Appendix with an asterisk. No effect reached significance in the analysis of FFD. In the analysis of FGD, however, there was a clear effect of both syllable length [short length, 335 msec; long length, 419 msec; $F(1,10) = 10.68$, $p < .01$] and number frequency [low frequency, 391 msec; high frequency, 363 msec; $F(1,10) = 5.17$, $p < .05$]. The effect of syllable length was more pronounced both in F values and in variance components. Because the same tendency was present for FFD, it was concluded that the slightly larger correlation between syllable length and the eye-fixation data (see Table 1) indeed indicated a predominance of syllable length over number frequency.

On the basis of the results of the 16 two-digit numbers, partial correlations for all 100 stimuli were calculated according to the following model: 1 = syllable length, 2 = number frequency, and 3 = number magnitude. The partial correlations according to this model are presented in Table 1, together with the final regression models for FFD and FGD. For FFD, only syllable length remained significant. For FGD, both syllable length and number frequency attained significance.

Discussion

In the introduction, it was argued that the effect of syllable length on number processing obtained by Pynte (1974) might have been an artifact of number frequency or number magnitude. Analysis of the numbers ranging from 0 to 99 indicated that these three variables are indeed highly correlated (correlations of .60 and more). The correlation between syllable length and number magnitude is inherent in the way Dutch (French, English) number names are constructed. The correlation between syllable length and number frequency is in line with word findings, where it has been shown that high-frequency words tend to be shorter than low-frequency words (see, e.g., Zipf, 1935, 1949). Therefore, Pynte's (1974) stimuli differed not only in number of syllables, but also with respect to number magnitude and probably number frequency.³ (See the Appendix.)

In order to control for confounding effects of number frequency and number magnitude, multiple regression analyses on eye-fixation data for all numbers smaller than 100 were run. This was preferred to the analysis of an artificial subset of numbers that orthogonally varied on each of the variables of interest (though see the Results section). The regressions indicated not only that syllable length explained most of the variance (16% for FFD, 46% for FGD) but also that the effect remained significant when the impact of number frequency and magnitude was partialled out. This was true for both FFD and FGD, which

seems to indicate that the phonological information is used from the first processing stages on. In addition, FGD was significantly influenced by the subjective frequency of the numbers. The effect of syllable length amounted to 13 msec per syllable for FFD and 25 msec for FGD. Mean FFD (266 msec) and FGD (404 msec) are comparable to values obtained in word reading (see, e.g., Inhoff, 1984; Rayner & Pollatsek, 1989, p. 115).

The successful replication of Pynte (1974) indicates, after elimination of potential artifacts, that phonological encoding is indeed part of visual processing in this task, as argued by, for instance, Rayner and Pollatsek (1989, p. 214), and Rossi (1985). The finding is the more compelling because vocalization was not required during the encoding stage in which eye movements were measured. However, it can be asked to what extent the results above relate to visual processing of numbers in general. First, the phonological encoding may have been provoked by the subsequent vocal recall of the numbers. Second, numbers were treated as character strings that merely had to be remembered and that in principle could have been replaced by any kind of symbols with a name. The more specific computational use of numbers (i.e., addition, multiplication) was not addressed. Both criticisms were dealt with in the next experiment.

EXPERIMENT 2

Experiment 2 tested whether the observed syllable-length effect in number processing would be present in a nonrecall task. In Experiment 1, vocalization was required for the output, and numbers constituted a nominal scale; that is, they were just labels that identified the elements of a population (Stevens, 1951). The normal computational use of numbers involves at least an ordinal scale and most often an interval or even a ratio scale. Therefore, Pynte's (1974) task was modified. Subjects again saw a series of three numbers ranging from 0 to 99, but this time they had to indicate manually whether the value of the middle number was between the values of the outer numbers. If the syllable-length effect could be obtained for this task as well, the evidence that phonological encoding is a necessary component of visual number processing would become stronger.

Method

Subjects. Eleven new subjects from the same population as that used in Experiment 1 participated. None wore glasses or lenses. All were unaware of the purpose of the study. The data of 4 additional subjects were excluded because of unsatisfactory eye-movement registrations.

Stimuli. Again, 100 trials of three random numbers were presented to all subjects. During these trials, all numbers ranging from 0 to 99 were presented once in the middle position. In half of the trials, the value of the middle number was between the values of the two outer numbers, which were randomly selected. In the other half, the value of the middle number was above or below the values of the outer numbers. Single-digit numbers were always coupled with other single-digit numbers, two-digit numbers with two-digit numbers. Each middle number had a .5 probability of falling be-

tween the other two numbers. This was not true for the numbers 0 and 10, which constituted the lower limit, or for 9 and 99, which constituted the upper limit; these values were always situated outside the range of the outer numbers. The stimuli were constructed in such a way that the processing of all three numbers was necessary for subjects to perform the task correctly. Each subject received a different stimulus constellation. Presentation occurred in the same way as it did in Experiment 1.

Task. The subjects were instructed to look at the fixation point on the left side of the screen until a stimulus was presented. Adequate fixation was ensured with the eye-movement system. As soon as the numbers appeared, the subjects had to read them silently from left to right. They had to press the right button if the value of the middle number was situated between the outer two, and the left button otherwise. The subjects were instructed to respond as soon as they knew the answer. The stimuli were presented until the subject reacted or for a maximal period of 2 sec. Trials in which eye-movement registration was deficient were repeated at a random place later in the series. This occurred on 11 out of a total of 1,100 trials.

Independent and dependent variables; Procedure. As in Experiment 1, the independent variables were syllable length of the number names, number frequency, and number magnitude. Raw data were transformed to fixations with the programs used in Experiment 1. The percentage of missing values amounted to 3.4% and was not correlated with any of the independent variables. FFD and FGD on the center number were analyzed. Reaction times were also collected, but they were not analyzed, because they were the result of many more factors than the one we were interested in (e.g., they involved identification and comparison of the three numbers, together with a correct manual response). The procedure was the same as it was in Experiment 1.

Results

The mean reaction time was 2.24 sec for all 1,100 trials, and it ranged from 1.76 to 3.60 sec for individual subjects. Error rate was 8.82%. No significant differences in eye-fixation data were found between correct and incorrect trials. Therefore, the remaining analyses are based on all trials (see note 1). Twenty-one missing cells (i.e., 1.9%) had to be estimated with the procedure from Yates (1933; see above). Mean FFD was 236 msec; mean FGD was 304 msec. FFD was not significantly shorter in Experiment 2 than it was in Experiment 1 [$F(1,20) = 3.44, p > .05$]; FGD, however, was [$F(1,20) = 12.05, p < .01$]. Mean FFD and FGD per number are presented in the Appendix.

Pearson correlation coefficients between the predictor variables and the eye-fixation data for Experiment 2 are listed in Table 2. The outline of this table is the same as that of Table 1. Only number magnitude was correlated significantly with FFD; the correlation between FFD and syllable length did not reach significance. For FGD, the correlations with number magnitude and with syllable length were significant (but see note 2). However, when the correlations were partialled out for the other effects, none of them remained significant.

As in Experiment 1, an ANOVA was run on the subset of 16 numbers for which the predictor variables were orthogonal, in order to have additional evidence of the relative importance of the three predictor variables (cf. the correlation between FGD and number magnitude is not much larger than the correlation between FGD and

Table 2
Raw Correlations, Highest Order Partial Correlations, and Partial Correlations
According to the Model for First-Fixation Duration and First-Gaze Duration
in the Number-Comparison Task (Experiment 2)

	Syllable Length	Number Frequency	Number Magnitude
First-Fixation Duration			
Raw correlation	.190	-.077	.224†
Highest order partial correlation	.108	.127	.149
Partial correlations model*	.043	.127	.224†
Final model: FFD = 223.14 + 0.25 Mag			
First-Gaze Duration			
Raw correlation	.231‡	-.072	.238‡
Highest order partial correlation	.176	.182	.139
Partial correlations model*	.089	.182	.238‡
Final model: FGD = 285.87 + 0.36 Mag			

Note—FFD = first-fixation duration. Mag = number magnitude. FGD = first-gaze duration. Syl = syllable length. Freq = number frequency. *Model: 1 = Mag, 2 = Syl, 3 = Freq. † $p < .05$, two-tailed. ‡ $p < .05$, two-tailed, according to the Fisher r -to- Z transformation, but not according to Lorch and Myers (1990).

syllable length). No effect reached significance in the ANOVA on FFD. In the analysis of FGD, there was an effect of both number magnitude [small numbers, 291 msec; large numbers, 320 msec; $F(1,10) = 6.46, p < .05$] and number frequency [low frequency, 289 msec; high frequency, 322 msec; $F(1,10) = 6.34, p < .05$]. No effect was present for syllable length [$F(1,10) = 1.49, p > .10$]. The variance component of number magnitude was also larger than the variance component of syllable length in the analysis of FFD.

Therefore, the order in which the variables were entered into the model for the regression analysis on all 100 numbers was: 1 = number magnitude, 2 = syllable length, and 3 = number frequency. Syllable length was entered before number frequency because of its larger correlation with the eye-fixation data in the regression analyses, and because the frequency effect in the ANOVA was not in line with other frequency effects reported in the literature. That is, FGD was longer for high-frequency numbers than for low-frequency numbers (see above). The partial correlations according to the model outlined above are presented in Table 2, together with the final models for FFD and FGD. In both models, only the effect of number magnitude remains significant. The effect of syllable length is negligible (less than 1% of the variance explained).

It might be wondered whether the shorter FGD in Experiment 2 as opposed to Experiment 1 (see above) was compensated for by more regressive gazes, so that the syllable-length effect has been underestimated by FGD. To check this possibility, correlations between the predictor variables and regressive gaze durations (RGD) were calculated. RGDs are the sum of all fixations after FGD. They could be due either to a refixation of the middle number after a regression to the first number, or to a regression from the third number. Although RGD was longer in Experiment 2 ($M = 260$ msec) than it was in Experiment 1 (117 msec), no correlation between RGD and the predictor

variables was larger than .10 ($n = 100, p > .20$). For syllable length, the correlation was even negative ($r = -.02$).

Another criticism might be that Experiment 2 did not provide the opportunity for the syllable-length effect to emerge that was provided by Experiment 1.⁴ It could be argued that subjects did not have to process the whole number in order to complete the task successfully, but that most of the time the first digit of the numbers was sufficient for the subjects to determine whether the middle number was between the other two in magnitude. For instance, a subject might decide whether the value of the middle number was situated between the outer two in a series "12 34 86" simply by looking at the first digits "1 3 8." This, of course, would eliminate any syllable-length effect in the regression analyses, because the range of syllable lengths would be reduced from six to two, with a clear predominance of monosyllabic "numbers."

To check the plausibility of this alternative explanation, a new analysis of the eye-movement data was performed. If subjects indeed used the strategy of only looking at the first digit, a rather clear prediction follows—namely, that a regressive eye movement will be made if there is a tie between first digits (e.g., when the series "21 23 95" is presented). Therefore, the mean number of saccades for different stimulus configurations was calculated (see Table 3).

There are nine possible saccades between the three numbers of a stimulus display; these saccades can be divided into refixations (i.e., a new fixation on the same number), progressions (i.e., from a number to the left to a number to the right), and regressions (from a number to the right to a number to the left). There were on the average 3.71 saccades (see the second to last line of Table 3). Two of these saccades were, not unexpectedly, progressions from the first to the second number, and from the second to the third number. Regressions were also quite common, and accounted for a mean of 1.31 saccades.

Table 3

Mean Number of Saccades between the Three Numbers (Divided into Refixations, Progressions, and Regressions), Sum of Saccades, Number of Observations, Percentage of Correct Responses, and Mean Correct Response Times (RT) to Different Stimulus Configurations in the Number-Comparison Task (Experiment 2)

	Saccades									Sum	N_{obs}	% Corr	RT _{corr}	Examples		
	Refixations			Progressions			Regressions									
	LL	MM	RR	LM	LR	MR	ML	RL	RM							
L = M = R	.21	.10	.01	1.06	.16	.91	<u>.38</u>	.42	<u>.52</u>	3.77	5.5	.96	2281	21	23	25
L = M < > R	.15	.07	.11	1.06	.18	1.01	<u>.35</u>	.34	.52	3.79	11.9	.91	2243	21	23	95
L = R < > M	.13	.10	.04	1.11	.11	.95	.38	.45	.45	3.72	8.2	.93	2164	21	95	23
M = R < > L	.15	.09	.05	.91	.16	.98	.37	.23	<u>.79</u>	3.73	11.8	.91	2405	95	21	23
*																
L ≈ M < > R	.10	.02	.09	.99	.16	1.00	.38	.35	.62	3.71	7.9	.92	2380	28	33	95
L ≈ R < > M	.13	.03	.03	.98	.13	.94	.54	.27	.62	3.67	5.2	.93	2281	28	95	33
M ≈ R < > L	.11	.07	.06	.92	.15	1.13	.27	.32	.74	3.77	8.2	.91	2163	95	28	33
L < > M < > R	.10	.05	.05	1.05	.12	1.01	.36	.31	.59	3.64	30.0	.91	2215	23	45	97
Single digits	.06	.21	.14	1.01	.04	1.00	.26	.26	.63	3.61	9.8	.91	2078	6	8	9
<i>M</i>	.13	.08	.06	1.01	.13	.99	.37	.33	.61	3.71	10.9	.92	2246			
<i>M</i> in Experiment 1	.27	.16	.14	1.09	.03	1.01	.16	.41	.31	3.58	12.2					

Note—L, M, and R = left, middle, and right numbers, respectively. “=” means same first digit. “≈” means first digits were different, but maximum difference in magnitude ≤ 10. “< >” means first digits were different and maximum difference in magnitude > 10. *L ≈ M ≈ R was not included because there were only 0.5 observations on the average.

However, if we look at the regressions for numbers with a tie between their first digits (see data underlined in Table 3), we see no difference from regressions for other stimulus configurations. If the second and the first numbers start with the same digit, there are, on the average, .37 regressions from the second to the first number, which is exactly the mean number of regressions for numbers that do not share the first digit. If the second and the third numbers start with the same digit, we have .52 regressions if all three numbers start with the same digit, and .79 regressions if only the second and the third numbers share the first digit. The figure of .79 is slightly above the mean value of .61 and therefore might give some support to the hypothesis of an increased need for regressions if numbers cannot be processed on the basis of the first digit alone. However, numbers that share the first digit are also closely related in magnitude. Therefore, the true control condition must consist of numbers that do not share the first number but are closely related in magnitude. An example would be “95 28 33,” in comparison with “95 21 23.” These data can be found in the seventh line of Table 3. For this control subsample, the mean number of regressions from the third to the second number amounted to .74, which is quite close to the .79 value found for numbers with the same first digit. Table 3 further shows that the lack of more regressions between numbers with the same digit did not result in higher error rates or very prolonged reaction times. Therefore, we think it can safely be concluded that the alternative strategy of only processing the first digits of numbers was not followed by the subjects of Experiment 2, and that the task dependence of the syllable-length effect in number processing is genuine.

For purposes of comparison, the mean number of saccades for Experiment 1 has also been included in the last line of Table 3. The mean number of saccades amounted

here to 3.58; two of these saccades were again progressions from the first to the second number, and from the second to the third number. For the rest, refixations tend to be higher and regressions lower. The former agrees with the larger FGD in Experiment 1 as opposed to Experiment 2.

Discussion

A nonrecall task in which numbers had to be compared was used to investigate whether the syllable-length effect would remain valid when vocalization was not required and numbers were presented on an ordinal scale. As in Experiment 1, possible confounding variables such as number frequency and number magnitude were controlled for by multiple regressions of the eye-fixation data based on all numbers smaller than 100.

Neither FFD nor FGD was predicted by syllable length, but both had significant correlations with number magnitude (see Table 2, but see note 2). The effect of number magnitude amounted to 0.25 msec per unit for FFD and 0.36 msec for FGD. It is not clear what exactly caused the relationship between number magnitude and gaze duration, but an analogous finding has repeatedly been reported in number-comparison studies (see, e.g., Potts et al., 1978). Reaction time for deciding which digit of a pair is larger declines with the difference in magnitude between the digits, but it increases as the magnitude of the smaller digit increases. One explanation of the latter effect is that the internal representation of number magnitude is a nonlinear, compressed (e.g., logarithmic) function of the magnitude of the number. In such a compressive spacing, large numbers are closer together on the internal scale than small numbers, so that pairs at the lower end of the continuum are more discriminable than pairs at the upper end (see also Krueger, 1989, pp. 256–258).

The greater difficulty in comparing large numbers may have resulted in longer gaze durations on large numbers than on small numbers, though additional experimental work is needed to confirm the hypothesis.

The failure to find a syllable-length effect in Experiment 2 runs against claims made by some authors (Rayner & Pollatsek, 1989, p. 214; Rossi, 1985) about the generality of Pynte's (1974) results. No phonological code is needed in number processing when vocalization is not required and numbers have to be compared. Arguments that the experimental task did not provide the opportunity for the syllable-length effect to emerge because the numbers did not have to be fully processed are not supported by the empirical data. The pattern of eye movements (refixations, progressions, regressions) remained stable for different ties among the numbers of a stimulus display (see Table 3), which suggests that the numbers were indeed processed completely during the first gaze.

GENERAL DISCUSSION

Two experiments were run to investigate the relationship between syllable length of number names and eye-fixation durations during silent reading of one- and two-digit numbers. In the first experiment, subjects had to read a series of three numbers and recall them orally; in the second experiment, subjects had to indicate manually whether the value of the middle number was between the values of the outer numbers. Special care was taken to make the control variables identical in both experiments (e.g., subjects from the same population; same equipment; same stimulus presentation; experiments run in the same 1-week period). Syllable length of number names accounted for 46% of the variance of first-gaze durations in Experiment 1, whereas it explained less than 1% of the variance in Experiment 2. This provides strong evidence for the claim that the phonological code of number names was assessed in the first experiment, but not in the second.

The syllable-length effect in number processing is regularly cited within the larger theoretical framework of the necessity of phonological recoding in visual processing (especially in word reading). Two opposing viewpoints prevail: Some authors claim that phonological recoding is an automatic and essential part of reading (e.g., Lukatela & Turvey, 1990; Perfetti, Bell, & Delaney, 1988; Rossi, 1985; Van Orden, Johnston, & Hale, 1988), whereas others consider the phonological route helpful but not imperative (e.g., Brysbaert & Praet, in press; Foster, 1990; Humphreys & Evett, 1985; Klapp, Anderson, & Berrian, 1973). At least for number processing, the latter view seems to be supported by the present study. Phonological recoding sometimes co-occurs with (silent) visual processing, but the activation (or at least the use) of the phonological code depends on specific task requirements. The fact that syllable length had an effect on first-fixation duration as well as on first-gaze duration in Experiment 1

suggests that the use of the phonological code occurs early in processing (Inhoff, 1984; Rayner & Pollatsek, 1987).

Task-dependent syllable-length effects have been reported for other stimuli as well. Klapp, Anderson, and Berrian (1973), who used words and pictures, found that response latencies increased with syllables for naming but not for categorization, which made them conclude that the syllable-length effect was due to response preparation. Similarly, Brysbaert and d'Ydewalle (1991) reported a larger effect of word length in a word-naming task than in a lexical decision task (but see Balota & Chumbley, 1984, and Hudson & Bergman, 1985).⁵

Response preparation need not be the only reason for the syllable-length effect. In their general discussion, Klapp et al. (1973) mentioned rehearsal as a second mechanism that might be likely to elicit implicit speech in visual perception. They argued that

implicit speech may be used for memory of individual words, whether in a rote learning situation or in a situation where meaning is not easily assigned to the word strings so that the Ss choose to remember the words in a rote fashion. . . . Perhaps implicit as well as overt speech represents a method of processing to increase memory rather than a mode of processing which mediates comprehension. (p. 373)

So, according to Klapp et al. (1973), speech may have been involved in Experiment 1 simply to help memory performance in a rote learning situation, which is known to be supported by rehearsal. New experiments are planned to investigate which of the two explanations is the more plausible.

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NOTES

1. In reaction time studies, it is common to analyze only the results of correct trials. However, in this experiment, an error in the oral recall could be due to factors other than the encoding of the middle number, the factor we are interested in. This might be the reason why there are no differences between correct and incorrect trials. The same is true for Experiment 2.
2. Exact p values are difficult to calculate in this kind of experiment, because data were not obtained from independent observations. The significance levels given, however, do agree with both the Fisher r -to- Z transformation for independent observations (Hays, 1988, pp. 590-593, 619-620) and the Lorch and Myers (1990) test of regression analyses of repeated measures data—except for the FGD data of Table 2, where the Fisher transformation suggests significance beyond the .05 level, whereas the Lorch and Myers test did not yield significance ($p > .10$).
3. The subjective frequency of the number "90" in the Appendix is artificially inflated because the experiment was finished at the end of 1990, and thus subjects had been regularly confronted with the number in the recent past. The same was not true for Pynte (1974).
4. The authors would like to thank Garvin Chastain for pointing them to this alternative explanation.
5. Syllable length and length in letters can be exchanged in this study, because both variables have an intercorrelation of .96.

APPENDIX

Number Magnitude, Syllable Length, Number Frequency, and Eye-Fixation Data for Experiments 1 and 2

Mag	Syl	Freq	Experiment 1				Experiment 2			
			FFD	SD	FGD	SD	FFD	SD	FGD	SD
0	1	430	241	123	365	218	229	95	249	77
1	1	465	227	77	251	68	256	108	335	143
2	1	435	221	61	231	53	205	58	243	126
3	1	405	204	82	265	107	235	81	264	80
4	1	375	208	81	310	186	212	70	234	76
5	1	420	205	51	262	99	226	67	315	162
6	1	365	193	88	243	99	230	94	249	86
7	2	360	209	111	205	116	221	69	278	89
8	1	355	209	74	262	48	235	116	285	105
9	2	400	248	89	326	225	196	92	284	133
10	1	445	275	146	312	141	188	109	240	124
*11 L	1 L	295 L	227	76	353	238	199	64	250	47
12	1	315	267	167	335	132	263	112	321	227
13	2	350	308	114	349	118	253	106	273	96

APPENDIX (Continued)

Mag	Syl	Freq	Experiment 1				Experiment 2			
			FFD	SD	FGD	SD	FFD	SD	FGD	SD
14	2	320	218	122	304	168	245	147	420	166
15	2	345	246	115	375	103	219	101	305	62
16	2	325	316	160	373	146	290	85	309	89
17	3	290	240	101	306	107	226	73	254	67
18	2	365	214	143	320	146	305	208	387	242
19	3	275	258	163	331	142	221	89	333	96
*20L	2L	370H	255	118	297	97	200	87	326	115
*21L	4H	340H	212	126	343	119	245	161	295	162
22	4	260	357	242	382	279	223	66	233	70
23	4	200	272	158	403	146	205	94	245	96
24	4	265	270	129	434	138	187	56	286	105
*25L	4H	370H	284	131	403	133	207	100	325	164
26	4	245	285	105	425	161	225	97	375	231
27	5	240	334	200	482	151	215	90	257	95
*28L	4H	225L	291	212	459	182	244	73	282	96
29	5	200	214	144	381	151	253	131	324	102
*30L	2L	320H	174	89	306	135	204	71	292	110
*31L	4L	140L	304	135	390	153	258	100	282	91
32	4	260	252	138	449	170	220	106	305	117
33	4	215	206	105	395	98	238	153	345	124
*34L	4H	205L	242	130	384	215	241	104	278	93
35	4	240	233	131	357	155	210	85	305	176
36	4	260	281	188	407	163	195	134	298	131
37	5	175	424	244	527	235	191	78	223	83
38	4	195	268	180	507	302	225	123	298	134
39	5	190	316	172	447	182	343	252	452	237
40	2	300	276	111	337	102	238	114	275	117
41	4	175	217	92	359	124	225	86	238	82
42	4	220	235	149	385	155	245	125	287	100
43	4	130	273	134	435	258	215	102	248	100
44	4	165	305	153	374	180	245	81	276	124
45	4	270	323	204	493	166	236	104	313	67
46	4	220	292	182	436	152	198	94	271	127
47	5	230	305	176	448	137	275	176	375	181
48	4	175	245	123	547	169	203	76	319	173
49	5	175	334	187	608	210	209	95	288	102
*50H	2L	330H	266	115	324	96	245	122	280	124
51	4	160	303	117	424	217	231	140	288	156
52	4	140	313	198	405	182	211	85	241	89
53	4	125	338	191	458	195	237	137	288	117
54	4	195	302	221	470	211	233	129	375	271
55	4	235	269	112	437	246	229	67	289	107
56	4	185	241	84	411	170	233	114	292	177
57	5	165	272	189	572	395	206	121	275	181
58	4	170	299	184	454	163	246	136	338	100
59	5	150	345	287	660	541	237	126	337	221
*60H	2L	290L	230	94	336	183	200	84	264	87
61	4	165	261	101	333	93	212	80	272	110
*62H	4H	165L	215	152	425	183	215	106	364	119
63	4	160	255	92	384	128	228	77	290	135
64	4	195	292	163	407	176	238	81	330	172
65	4	200	269	164	398	162	265	116	344	191
66	4	215	202	94	343	155	192	67	256	67
67	5	195	316	232	503	220	352	322	420	302
68	4	235	301	198	520	190	206	103	349	182
*69H	5H	325H	280	136	402	189	307	153	420	186
70	3	245	278	112	372	123	229	149	322	166
71	5	240	262	127	332	135	300	218	348	215
72	5	220	225	98	396	146	275	123	298	121
*73H	5H	145L	349	192	466	122	208	117	243	100

APPENDIX (Continued)

Mag	Syl	Freq	Experiment 1				Experiment 2			
			FFD	SD	FGD	SD	FFD	SD	FGD	SD
74	5	200	235	122	495	155	211	99	330	240
*75H	5H	360H	360	182	474	189	226	82	317	114
76	5	190	261	159	535	246	204	93	300	148
77	6	200	241	107	325	126	296	261	296	261
78	5	140	386	224	579	159	228	84	274	93
79	6	155	240	138	417	150	228	149	305	152
*80H	2L	260L	203	76	318	101	269	143	351	149
81	4	205	253	171	358	174	238	92	316	119
82	4	170	271	125	359	137	238	107	300	89
83	4	145	244	132	469	141	258	114	314	103
84	4	215	282	163	460	105	265	95	293	94
85	4	200	280	178	486	168	206	90	283	117
86	4	150	253	97	506	179	205	78	303	128
87	5	145	295	227	497	260	268	162	313	138
88	4	205	236	102	391	171	260	121	297	113
89	5	235	281	173	455	137	244	93	320	160
*90H	3L	360H	256	164	359	155	255	83	321	103
91	5	235	246	139	425	216	240	97	279	98
92	5	245	213	144	359	164	295	105	305	120
93	5	150	253	114	439	177	202	101	337	219
94	5	165	283	169	519	249	321	135	365	123
95	5	245	223	116	481	224	225	158	302	179
96	5	200	305	212	490	193	273	148	316	122
97	6	160	243	123	461	203	278	117	345	124
98	5	205	317	179	495	153	215	58	308	98
99	6	280	235	115	312	129	215	79	310	92

Note—FFD = first-fixation duration. FGD = first-gaze duration. *Indicates a number of the number subset on which the ANOVA was conducted; L and H stand, respectively, for low and high value for the predictor variables number magnitude (Mag), syllable length of the number name (Syl), and number frequency (Freq).

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