PRODUCING COMPLEX SPOKEN NUMERALS FOR TIME AND SPACE

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PRODUCING COMPLEX SPOKEN NUMERALS FOR TIME AND SPACE

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op het gebied van de Sociale Wetenschappen

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te Heerlen

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Voor mijn ouders

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Marjolein.

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INTRODUCTION

CHAPTER 1

Complex[1] numerals are omnipresent in our world. The combination of two or more digits can represent all sorts of information, which is needed for answering mundane questions in everyday conversation such as “what’s your phone number” (0243881295), “what’s the zip code of your home address?” (6581HW), “what is your birthday?” (20071978), “what time is it?” (13:30) etcetera. To answer these questions, one would typically respond in Dutch with “nul vierentwintig drie acht acht een twee negen vijf” “vijfenzestig eenentachtig HW”, “twintig zeven negentienachtenzeventig”, “half twee” and soforth.

Importantly, these types of expressions have well-defined morpho-syntactic structures, with a fixed position coding for the digits comprising the complex numeral. For instance, the first two and last two digits in a zip code are grouped together for pronunciation, whereas the digits comprising a phone number are mostly produced as single numerals. Conventions of how to pronounce complex numerals may vary between linguistic cultures and professions. The digital clock time of 13:30, for example, would be named as “half twee” (English “half past one”) by speakers of Dutch, as “one thirty” by American English speakers, and as “thirteen hundred thirty” by military personnel.

[1] Multi-digit numbers are meant here, not to be confused with the mathematical definition of complex numbers (i.e., $x+iy$, where x and y are real numbers and i is the imagninary unit equal to the square root of -1).

What's more, a set of two or more digits can at the same time code several kinds of information. The complex numeral consisting of 2, 4, and 5 can represent either the dimension of time (the clock time 2:45) or the dimension of space (the house number 245). However, although the visual input is almost identical for these two modes of response, the multi-morphemic utterances that are generated to describe these cognitive domains are substantially different (e.g., "quarter to three" vs. "two hundred forty-five", respectively). Furthermore, whereas the digits and their relative position in the input can be directly mapped onto the slots to be filled for house number expressions, the production of clock time expressions from a digital input is less transparent. For example, in Dutch, 2:30 will be pronounced as "half drie" (English "half past two"), with none of the digits in the digital clock time being mentioned as such in the subsequent clock time expression.

SPOKEN PRODUCTION OF COMPLEX NUMERALS FOR TIME AND SPACE

Thus, although the three-digit complex numerals for the domains of time and space are comparable in visual input, the resulting multi-morphemic utterances generated by the speaker are quite different. Furthermore, the way in which the information from the digital input is incorporated in the subsequent multi-morphemic utterance is less transparent for clock times than for house numbers. Given such differences, it is plausible to assume that these two modes of response (house number vs. clock time) also differ with respect to the components of speech planning involved. This thesis is aimed at systematically testing this assumption by looking at different input formats (e.g., Arabic digit, alphabetic) and expression types (e.g., house numbers vs. clock times).

The working model (Figure 1) for the spoken production of complex numerals for time and space developed in this dissertation has been adapted from Levelt, Roelofs, and Meyer's (1999) theory on single word production. This theory holds that the planning of words is a staged process, proceeding from conceptual preparation to articulation initiation. Three major planning levels (left part of Figure 1) can be distinguished: conceptual preparation, lemma retrieval, and form encoding. Conceptual preparation concerns the activation and selection of lexical concepts for the utterance. Lemma retrieval involves retrieving memory representations of the syntactic properties of the words to be expressed. After the lemma has been selected, the form of the utterance is encoded, which includes access to morphological, phonological, and phonetic information about the word. Finally, the corresponding motor programs are recovered for articulation.

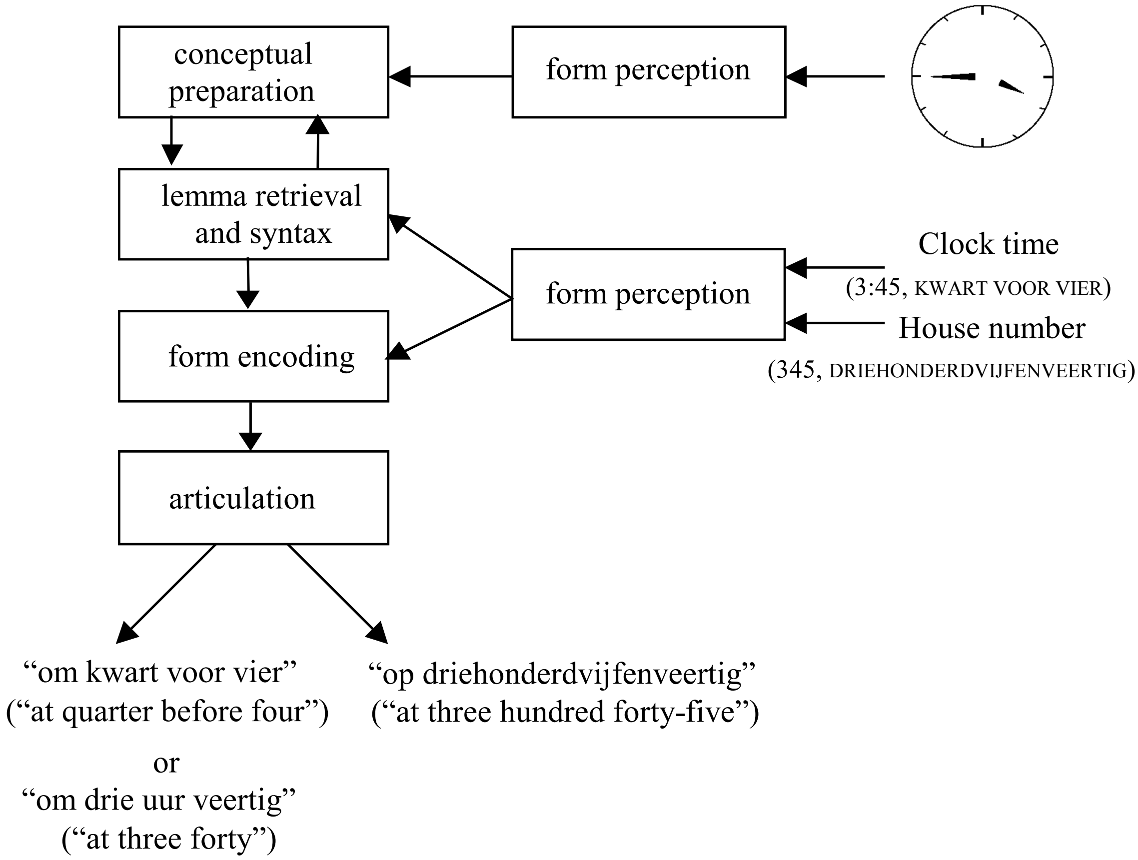

Figure 1. *Planning levels involved in complex numeral production.*

According to this model, complex numerals are constructed and represented as composite number concepts and lemmas. When generating complex numerals (e.g., 230), a composite number concept is used to retrieve the corresponding lemmas (e.g., 200 and 30), which are syntactically ordered. Then the appropriate form is constructed, by retrieving morphemes and segments, constructing phonological syllables, and retrieving the motor programs for articulation. This model predicts that different routes through the speech production system are adopted depending on the mode of response, input format, and type of expression used.

CLOCK TIMES

Producing relative time expressions (e.g., "quarter to four") from an *analog* clock involves both conceptual and morphophonological speech planning, as illustrated in Figure 1. Relative time expressions, which are most commonly used to convey time in Dutch, mention the minute before the hour information, whereas for absolute time expressions ("three forty-five") this order of mention is reversed (cf. Bock, Irwin, Davidson, & Levelt, 2003). The conceptual involvement concerns extraction of the hour (i.e., 4) and minute (i.e., 45) information from the small and big hands, and subsequently conceptualizing the reference point (i.e., coming hour) and distance in minutes from that reference point (i.e., fifteen minutes). Next, the corresponding lemmas need to be retrieved (i.e., *quarter*, *to*, and *four*) and syntactically ordered. Finally, the corresponding morphemes (e.g., <quarter>) and phonemes need to be retrieved, syllabified, and the motor programs need to be recovered.

Likewise, producing relative time expressions from a *digital* clock (e.g., 3:45) involves some conceptual level planning. After extracting the hour and minute information from the digits in the input, the reference point (i.e., coming hour) and the distance in minutes from that reference point (i.e., fifteen minutes) are conceptually determined, the corresponding lemmas (i.e., *quarter*, *to*, and *four*) are retrieved, syntactically ordered, the morphemes and phonemes are retrieved, syllabified, and the motor programs are recovered.

Thus, in this model, equivalent speech planning levels are engaged for producing relative time expressions from analog and digital clocks. However, when time is told by producing *absolute* time expressions (e.g., "three forty-five") or from alphabetic input format (e.g., kwart voor vier, reading aloud), the model holds that a different route through the speech production system is adopted. For instance, when producing absolute time expressions from a digital clock (i.e., 3:45) it suffices to read the digits from the input, and subsequently to retrieve the corresponding lemmas (i.e., *three*, *forty-five*), recovering the morphemes (i.e., <three>, <forty>, and <five>), retrieving the phonemes, syllabifying them, and recovering the motor programs. Hence, no conceptual level speech planning is needed for producing absolute time expressions or for reading aloud relative time expressions from alphabetic input (see Figure 1).

HOUSE NUMBERS

Similarly, for canonically naming a complex Arabic numerals such as 345 (e.g., as house number) it suffices to determine the hundreds, tens, and ones from the input, retrieving and ordering the corresponding lemmas (in Dutch the ones are mentioned before the tens in the utterance), recovering the morphemes <three>, <hundred>, <forty>, and <five>, retrieving their phonemes, syllabifying them, and recovering the motor programs (see Figure 1). Likewise, reading aloud the alphabetically written numeral driehonderdvijfenveertig may be achieved by retrieving the corresponding morphemes <three>, <hundred>, <forty>, <five>, respecting the order in the input, retrieving their phonemes, syllabifying them, and retrieving the motor programs. (Alternatively, the phonemes may be retrieved through application of grapheme-phoneme correspondence rules, after which the phonemes are syllabified and the motor programs are recovered for articulation).

Thus, this model on complex numeral production claims that conceptual level preparation is not required for house number naming and reading. Hence, a conceptual variable like the magnitude of the numeral should not play a role in naming and reading house numbers. So far, the influence of magnitude has only been examined for numerals up to 99 (Brysbaert, 1995). This thesis goes beyond this range by investigating naming and reading aloud of 3-digit complex numerals.

STRUCTURE OF THE THESIS

The first part of the thesis (Chapters 2 and 3) is mainly concerned with the different planning levels that are involved when complex numerals are being produced as clock times or as house numbers. Several reaction time and eye-tracking studies are reported that addressed the differences in speech planning when complex numerals have to be named (from Arabic digit format) or read aloud (from alphabetic format). The second part of the thesis (Chapters 4 and 5) reports reaction time and priming studies looking in more detail at time telling by contrasting different clock displays (analog vs. digital clocks) and alternative means of conveying time (relative vs. absolute time expressions).

Chapter 2 reports a series of reaction time experiments investigating the planning levels that are involved in naming and reading complex numerals. For naming (Experiment 1), the 3-digit Arabic input presented on the screen (e.g., 245 or 2:45) was either named as house number ("tweehonderdvijfenveertig" literally "two hundred forty-five") or as clock time (i.e., "kwart voor drie" literally "quarter to three"). Likewise for reading aloud (Experiment 2), speakers read aloud house numbers and clock times from alphabetic input format (e.g., tweehonderdvijfenveertig or kwart voor drie), which resulted in a similar speech output as for naming (i.e., "tweehonderdvijfenveertig" literally "two hundred forty-five" or "kwart voor drie" literally "quarter to three"). The model predicts that the levels of speech planning involved differ between input format (alphabetic vs. Arabic digit) and mode of response (house numbers vs. clock times).

In Chapter 3, the speech planning levels that are engaged in complex numeral production were investigated further in two eye-tracking experiments. Speakers named (Experiment 1) or read aloud (Experiment 2) pairs of house numbers and clock times while their eye movements and speech were monitored. The aim was to examine whether gaze durations would reflect, in a similar manner as found earlier for response latencies in Chapter 2, the different speech planning levels (from conceptual preparation to morphophonological encoding) that are involved in the naming and reading of complex numerals for time and space.

In Chapter 4, the conceptual operations (such as determining the utterance referent and the relative distance in minutes) that are involved in Dutch time telling were explored in more detail with a repetition-priming paradigm. Speakers first told the time from an analog clock (the prime) and directly thereafter they told the time from a digital clock (the target). Primes differed from targets both on the hour and the minute dimension such that there was no speech overlap between prime and target. If aspects of conceptual transformations are shared between naming analog and digital clocks, priming effects should be obtained.

Chapter 5 reports a reaction time study in which different expression formats for conveying time (absolute versus relative time expressions) were contrasted with alternative clock displays (analog versus digital clocks). The model predicts that which particular levels of speech planning are involved in time telling is mainly determined by the expression format used to convey the time rather than by the clock displays used to tell time. Finally, in Chapter 6, the results from the previous chapters are summarized and discussed in a broader perspective.

METHOD OF ANALYSIS

The analyses reported in this thesis involved multi-level multiple regression modeling (Baayen, submitted; Pinheiro & Bates, 2000; Lorch & Myers, 1990), using the R statistical programming environment version 1.7.0 (available at http://lib.stat.cmu.edu/R/CRAN/), which was carried out on the total data sets (both response latencies and gaze durations) for naming and reading aloud complex numerals as house numbers and clock times.

This method of multi-level regression modeling allowed me not only to assess the relative contributions of each planning stage (from conceptual preparation to word form encoding) to the data, but also to control for any existing covariances between speech planning variables and to partial out effects of learning and fatigue.

PLANNING LEVELS IN NAMING AND READING COMPLEX NUMERALS

CHAPTER 2

Marjolein Meeuwissen, Ardi Roelofs, and Willem J. M. Levelt[1]

ABSTRACT

On the basis of evidence from studies of the naming and reading of numerals, Ferrand (1999) argued that the naming of objects is slower than reading their names, due to a greater response uncertainty in naming than in reading, rather than to an obligatory conceptual preparation for naming, but not for reading. We manipulated the need for conceptual preparation, while keeping response uncertainty constant in the naming and reading of complex numerals. In Experiment 1, participants named three-digit Arabic numerals either as house numbers or clock times. House number naming latencies were determined mostly by morphophonological factors, such as morpheme frequency and the number of phonemes, whereas clock time naming latencies revealed an additional conceptual involvement. In Experiment 2, the numerals were presented in alphabetic format and had to be read aloud. Reading latencies were determined mostly by morphophonological factors in both modes. These results suggest that conceptual preparation, rather than response uncertainty, is responsible for the difference between naming and reading latencies.

[1] Slightly adapted version of this chapter has been published in *Memory & Cognition, 31:8* (2003), pp. 1238-1248.

INTRODUCTION

The naming of objects usually takes longer than reading their names. Cattell (1886) was the first to measure this difference in latency between naming and reading, which he explained in terms of greater practice for reading than for naming. However, a study by Brown (1915) showed that even after 10 days of practice in naming, reading was, on average, 131 msec faster than naming. Ligon (1932) investigated the effect of practice by examining the development of the difference between reading and naming in a large group of school children whose ages varied from 6 to 16 years. Naming and reading times decreased with age, but the difference between naming and reading remained constant (286 msec, on average). Given that the difference was present from the outset, it seems that a differential amount of practice between naming and reading is not the crucial factor.

Stroop (1935), however, contested Ligon’s conclusion. On the basis of the observation that practicing color naming yields interference from incongruent colors in word reading, he argued that, as a consequence of different amounts of training, “the word stimulus has been associated with the specific response 'to read', while the color stimulus has been associated with various responses: 'to admire', 'to name', 'to reach for', 'to avoid', etc.” (p. 660).

Fraisse (1967, 1969) showed in a series of experiments that more time is required to name than to read one and the same stimulus. He used the sign O and had participants either read it as “oh” or name it as “circle”. He found a latency difference of about 100 msec between naming and reading. Following Stroop (1935), he assumed that the difference reflected a higher degree of uncertainty in terms of number of alternatives in naming, as compared with reading. More recently, Theios and Amrhein (1989) reviewed the literature concerning the time difference between naming and reading, and they estimated the difference in time to be 160 msec, on average. Theios and Amrhein argued that the difference between naming and reading is due to both the number of possible response alternatives (Stroop, 1935; Fraisse, 1967, 1969) and a difference in functional architecture. In particular, they argued that reading a word aloud entails a fast process of transcoding a stimulus into the required articulatory response by means of grapheme-to-phoneme transformations, without necessarily accessing the mental lexicon. By contrast, naming a picture requires additional planning -- namely, selecting or computing the meaning of the depicted object (*conceptual preparation*) and selecting the correct name from other plausible alternatives.

Ferrand (1999) empirically contrasted response uncertainty and conceptual preparation by using Arabic numerals, ranging from 1 to 20, for naming and reading. A crucial attribute of Arabic numerals, which they share with their written names, is that there is no response uncertainty. That is, a given Arabic numeral represents only one precise magnitude and corresponding response. Given the same degree of uncertainty in the case of Arabic numerals and the corresponding written number words, reading and naming times should be equal, which was indeed what Ferrand observed. This suggests that response uncertainty, rather than obligatory conceptual preparation, is the crucial factor (cf. Stroop, 1935).

However, Ferrand's (1999) argument presumes that the naming of Arabic numerals requires conceptual preparation, just like object naming (cf. Brysbaert, 1995; McCloskey, 1992), but that does not need to be the case (Cipolotti & Butterworth, 1995; Dehaene, 1992). It may be the case that Arabic numerals and written number words are processed in a similar way, different from that for pictures (Roelofs, submitted). In the theory for word production advanced by Levelt, Roelofs, and Meyer (1999; Roelofs, 1992, 1997, 2003) -- henceforth, LRM -- the reading of words can be achieved without conceptual preparation, whereas picture naming obligatorily engages the conceptual level. Roelofs (2003) showed that an implemented model for this theory, WEAVER++, accounts for a wide range of findings on the naming of colors/objects and reading their names.

The LRM theory holds that the conceptually driven planning of words is a process with stages, leading from conceptual preparation to the initiation of articulation. Three planning levels can be distinguished (Figure 1): conceptual preparation, lemma retrieval, and form encoding. Conceptual preparation is the activation and selection of lexical concepts for the utterance. Lemma retrieval involves the retrieval of memory representations of the syntactic properties of the words to be expressed. After a lemma has been selected, the form of the utterance is encoded, which includes access to morphological, phonological, and phonetic information about the word.

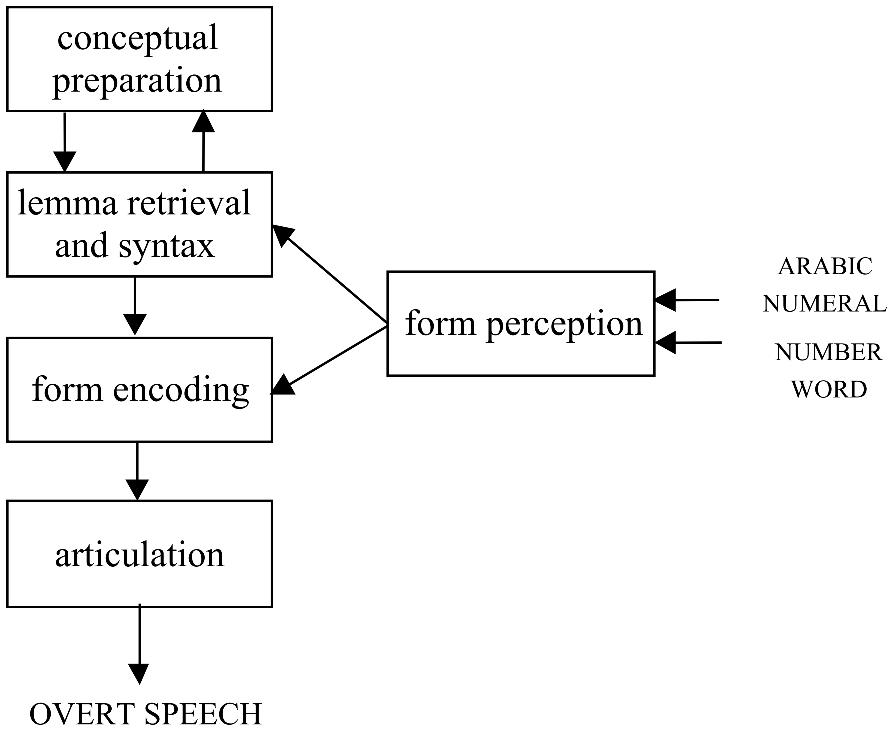

Figure 1. *Planning levels in spoken numeral production, following Levelt, Roelofs, and Meyer (1999; Roelofs, submitted).*

Empirical evidence in support of these levels of representation in numeral production comes from chronometrical evidence from our laboratory (Roelofs, submitted) and speech errors. For example, Sokol and McCloskey (1988) have reported a single case study on patient J.S., who had no problem understanding numerals but made errors in both speaking and writing them. J.S.'s impairment was characterized by numeral-syntax and morpheme errors. The numeral-syntax errors made by J.S. were quite comparable in amount and nature for spoken and written numeral production. For example, when presented with the complex numeral 146,359, he erroneously responded with “one hundred thousand forty-six three hundred fifty-nine” in both output modalities. In contrast, J.S.' morpheme substitution errors were in the spoken modality, rather than in written numeral production. For example, he responded “*six* hundred nine” to the visually presented numeral 309 but correctly wrote “three hundred nine”. These findings are in line with the LRM theory's notion of a modality-independent process of lemma retrieval and construction and a modality-specific process of form encoding.

The LRM theory holds that complex numerals are constructed and represented as composite number concepts and lemmas. In the conceptually driven generation of complex spoken numerals, a composite number concept is used to retrieve the corresponding lemmas, which are then syntactically ordered. Next, the appropriate form is constructed, which includes retrieving morphemes and segments, constructing the appropriate phonological syllables, and retrieving motor programs for these syllables. For example, telling the time from an analog clock in Dutch minimally involves conceptually determining the reference point (full hour, half hour, or coming hour) and the distance from the reference point in minutes. Next, the corresponding lemmas need to be retrieved (e.g., *kwart*, English *quarter*; *voor*, English *to*; and *drie*, English *three*) and syntactically ordered. Finally, the corresponding morphemes (e.g., <kwart>) and phonemes (/k/, /w/, etc.) need to be retrieved, the phonemes should be syllabified, and the corresponding motor programs need to be recovered.

In contrast, for canonically naming a complex Arabic numeral such as 245 (e.g., as a house number) in Dutch, it suffices to determine the hundreds, tens, and ones from the input, retrieving and ordering the corresponding lemmas (in Dutch, the ones are mentioned before the tens in the utterance), recovering the morphemes <twee>, <honderd>, <vijf>, <en>, and <veertig>, retrieving their phonemes, syllabifying them, and recovering the motor programs. Similarly, reading aloud the alphabetically written numeral TWEEHONDERDVIJFENVEERTIG may be achieved by retrieving the corresponding morphemes <twee>, <honderd>, <vijf>, <en>, and <veertig>, respecting the order in the input, retrieving their phonemes, syllabifying them, and recovering the motor programs. Alternatively, the phonemes may be retrieved through application of grapheme-phoneme correspondence rules, after which the phonemes are syllabified and the corresponding motor programs are recovered. Whether one or two nonconceptual routes (i.e., a lexical-form route and a grapheme-to-phoneme route) exist for reading words is hotly debated (e.g., Coltheart, Curtis, Atkins & Haller, 1993; Coltheart, Rastle, Parry, Langdon, & Ziegler, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996). The discussions of this issue have concentrated on reading morphologically simple, monosyllabic words. Not much is known about reading complex numerals, which are polysyllabic, morphologically complex words. The issue of planning routes in reading complex numerals is addressed in the present article.

Our theory holds that, unlike canonically naming complex Arabic numerals as house numbers, naming Arabic numerals as clock times demands conceptual preparation. Naming digital clock times (e.g., 2:45) involves determining the hours and minutes from the input, conceptually determining the reference point (for 2:45, this is the coming hour) and the distance from the reference point in minutes (i.e., 15), retrieving the corresponding lemmas (the lemma *kwart* for 15 and the lemmas of *voor* and *drie*) and syntactically ordering them, retrieving the corresponding morphemes and phonemes, syllabifying the phonemes, and recovering the corresponding motor programs.

To test between the response uncertainty and the conceptual preparation explanations of the difference in reading and naming times, we compared the naming of complex Arabic numerals and the reading of the corresponding names. In Experiment 1, participants named all three-digit Arabic numerals between 200 and 955 ending with a 0 or 5, either canonically as house numbers or as clock times -- henceforth referred to as *mode*. For example, the participants produced the Dutch equivalent of “two hundred forty-five” in response to 245 and “quarter to three” to 2:45. In Experiment 2, the participants simply had to read aloud the numerals presented in alphabetic format, again as house numbers and as clock times. For example, they said (in Dutch) “two hundred forty-five” in response to TWO HUNDRED FORTY-FIVE and “quarter to three” in response to QUARTER TO THREE.

With respect to house number naming in Experiment 1, the LRM theory predicts that lemma and word-form level factors, such as the morphophonological length of the utterance, will mostly determine naming latencies, because a nonconceptual route suffices for naming the Arabic numerals. In contrast, in the case of digital clock time naming, the theory predicts that conceptual level factors will additionally determine naming latencies. In Experiment 2, in which the numerals had to be read aloud, we would expect no conceptual involvement whatsoever for both modes of response. Therefore, we would predict that factors operating at the lemma and word-form encoding level will determine naming latencies in both response modes. In contrast, if response uncertainty determines the difference in time between reading and naming (Ferrand, 1999), the naming latencies should not differ between the modes and the input formats, because uncertainty would be held constant among these conditions.

EXPERIMENT 1

In the first experiment, we tested our theory's prediction that the latencies for naming house numbers should be determined mainly by morphophonological factors, whereas the latencies for naming clock times should exhibit a strong conceptual involvement. In contrast, under the uncertainty account (Ferrand, 1999), there should be no difference between the response modes.

METHOD

Participants

Thirty speakers participated in the experiment. They were undergraduate students at Nijmegen University and native speakers of Dutch and had normal or corrected-to-normal vision. They were paid for their participation.

Materials

The stimuli consisted of three-digit Arabic numerals ranging from 200 to 955 and ending either with a 0 or a 5. Collapsed across the hundreds and the hours, this yielded 12 different number types: (00) 200, 300, … (05) 205, 305, … (10) 210, 310, … (15) 215, 315, … (20) 220, 320, … (25) 225, 325, … (30) 230, 330, … (35) 235, 335, … (40) 240, 340, … (45) 245, … (50) 250, … (55) 255… For each type, there were eight instances (e.g. for type [00], the instances were 200, 300, 400, 500, 600, 700, 800, 900). Note that numerals ranging from 100 to 155 were excluded from the stimulus set. For numerals in the interval of 100-199, no explicit information is encoded in Dutch utterances about which particular hundred is involved. For instance, in Dutch, the numeral 105 is pronounced as "honderdvijf" (hundred five), whereas the numeral 205 is pronounced as "tweehonderdvijf" (*two* hundred five). Furthermore, we controlled for possible voice key artifacts by instructing the participants to start each response with the same word, *op* (at) for the house numbers and *om* (at) for the clock times. In this way, the responses in all the conditions started with the same phoneme. In Dutch, there are three utterance referents for clock times (full hour, half hour, and coming hour) rather than the two in English, yielding utterances in Dutch like "vijf voor half vier" (literally, "five to half four") rather than utterances like "three twenty-five" in English.

With respect to the instruction to name clock times in the relative way, only the number types (20) and (40) have two naming options. For example, 2:40 can be named as "tien over half drie" (literally, "ten past half three") and as "twintig voor drie" (literally, "twenty before three"), the latter being infrequent. To make sure that there was no response uncertainty, given the instructions, we asked the participants before each experiment to name several prototypes of the clock times in a relative way (the standard way for telling time in Dutch, in contrast to the absolute way, which is standard in American English). All the participants responded correctly for all clock types 100% of the time. Crucially, they all named the number types (20) and (40) in the most common way -- for example, 2:20 as "tien voor half drie" (literally, "ten before half three") and 2:40 as "tien over half drie" (literally, "ten past half three"). So it is safe to assume that in our experiment, there was no response uncertainty for the clock times.

Design

Each mode (house number or clock time) was tested in a separate block of trials. Each experimental block randomly presented the 96 stimuli (12 types x 8 instances), which were repeated three times, yielding 288 trials per mode. A practice block of 12 trials, containing items of each stimulus type, preceded a block of trials. The order in which each response mode was tested was counterbalanced across participants.

Procedure

The participants were tested individually. They were seated in a dimly lit, soundproof cabin, in front of a computer monitor (NEC Multisync) and a Sennheiser microphone. The distance between the participant and the screen was approximately 50 cm. The experiment was run with the NESU experimental software developed at the Max Planck Institute. Naming latencies were measured using a voice key apparatus. Preceding each experimental block, the participants were provided with a written instruction stating how the three-digit numbers had to be named (either as house numbers or as clock times). Furthermore, they were asked to respond in a fluent manner.

The structure of a trial was as follows. First, the participant saw a warning signal (an asterisk) for 200 msec, directly followed by the display of a three-digit Arabic number for 100 msec. The stimuli were presented in black on a white background. Before the next trial started, the screen went blank for another 1.4 sec. The total duration of the trial was 1.7 sec. Naming latencies were collected for each participant individually. Each trial was recorded using a DAT recorder. An experimental session lasted about 20 min.

Analyses

A trial was considered invalid when it included a speech error, a voice key error or a time-out or when a wrong oral response was given. Invalid trials were excluded from the statistical analyses. Furthermore, voice key errors and time-outs were excluded from the error analyses. Voice key errors and time-outs occurred, respectively, in 1.3% and 0.1% of the trials in the house number mode and in 0.8% and 0.2% of the trials in the clock time mode.

RESULTS

Table 1 gives the mean naming latencies, the standard deviations, and the percentages of errors for the house number and clock time modes. Figure 2 shows the mean naming latencies for the 12 number types in the house number mode (upper panel) and the clock time mode (lower panel).

Errors

The participants made fewer errors in the house number mode than in the clock time mode [$F_1(1, 29) = 38.57$, $p < .0001$; $F_2(1, 84) = 66.53$, $p < .0001$]. Errors varied depending on the number type [$F_1(11, 319) = 5.29$, $p < .0001$; $F_2(11, 84) = 4.01$, $p < .0001$]. Furthermore, the effect of number type depended on the mode [$F_1(11, 319) = 3.75$, $p < .0001$; $F_2(11, 84) = 3.89$, $p < .0001$]. As indicated by Table 1, most errors were made in the slowest conditions, so there is no evidence for a speed-accuracy tradeoff.

Table 1. *Mean Naming Latencies (in Milliseconds), Standard Deviations, and Percentages of Errors (E%) per Mode and Type for Experiment 1,With Naming of House Numbers and Clock Times Presented in Arabic Format.*

	Mode					
Type	House number			Clock time		
	M	*SD*	*E%*	*M*	*SD*	*E%*
00	438	100	0.6	530	86	0.1
05	449	99	1.7	580	111	2.2
10	455	105	1.9	585	113	1.9
15	460	108	1.1	592	114	2.1
20	457	108	1.7	690	156	5.3
25	463	105	1.7	664	151	4.6
30	460	111	1.4	626	127	2.8
35	463	106	1.1	655	141	4.0
40	459	104	0.8	684	159	6.3
45	463	109	2.1	624	127	3.3
50	457	105	0.8	655	132	5.3
55	463	110	2.5	628	124	5.4
Total	457	106	1.4	626	128	3.6

Naming latencies

Naming latencies were, on average, 169 msec shorter in the house number mode than in the clock time mode [$F_1(1, 29) = 134.48$, $p < .0001$; $F_2(1, 84) = 8967.61$, $p < .0001$]. Moreover, the latencies depended on type[2] [$F_1(11, 319) = 50.50$, $p <$

[2] By using the factor type, a global comparison can be made between the two different modes of response (house number vs. clock time).

.0001; F_2 (11, 84) = 86.90, p < .0001]. Furthermore, the effect of type varied with mode [F_1(11, 319) = 33.20, p < .0001; F_2(11, 84) = 47.23, p < .0001].

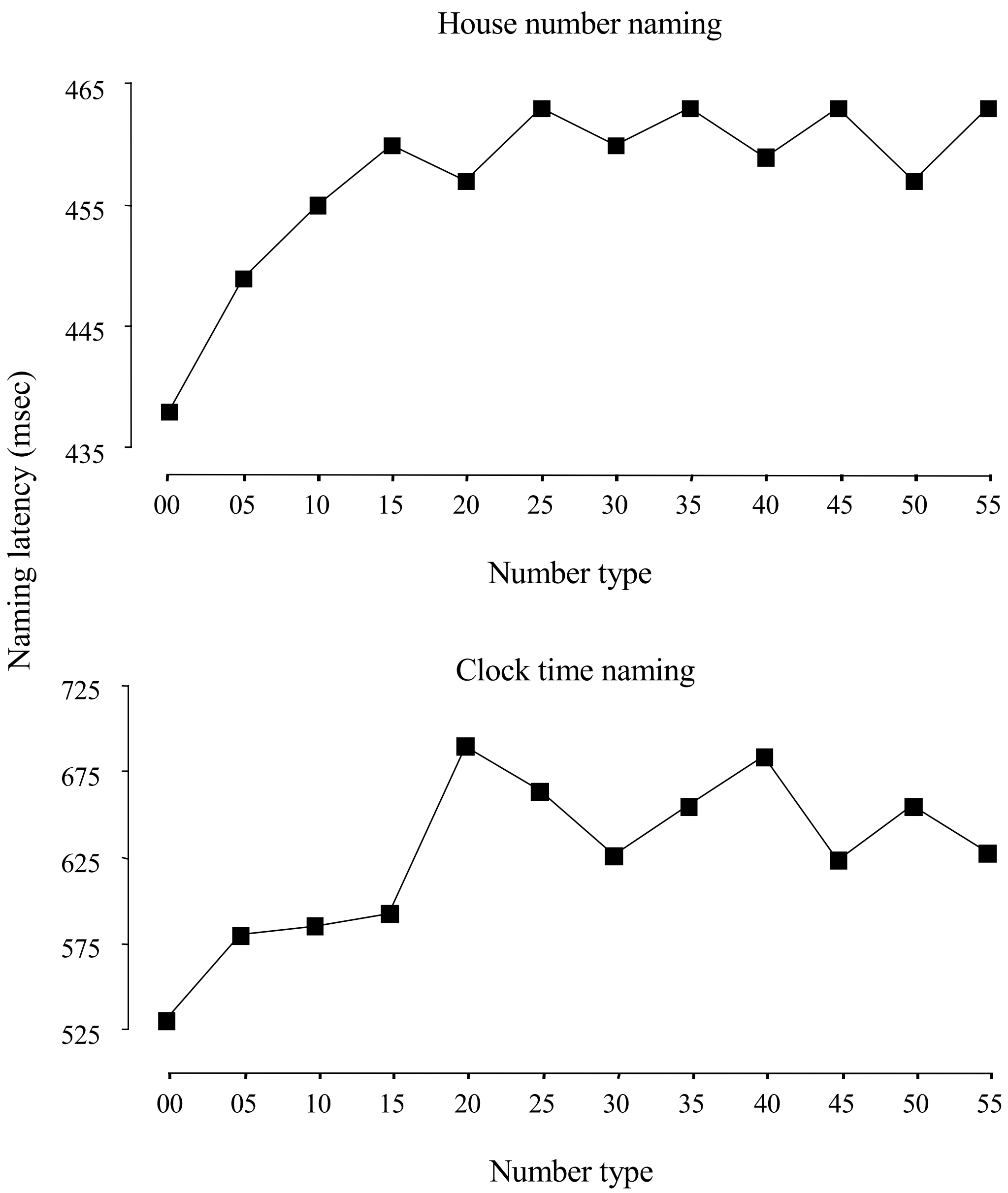

Figure 2. *Latencies, in milliseconds, for the naming of house numbers and clock times in Arabic format in Experiment 1.*

To gain further insight in the factors underlying the interaction between type and mode, we ran multiple regression analyses over the total data set. The following groups of predictor variables were entered into the analyses: (1) magnitude information (absolute magnitude of the whole number displayed and absolute magnitude of the last two digits and its logarithm [suggested by Wim Fias, personal communication, November 12, 2002]), (2) numeral length (number of morphemes, number of syllables, and number of phonemes), and (3) frequency: logarithm of the whole-form frequency (estimated from CELEX database [Baayen, Piepenbrock, & Gulickers, 1995] for the house numbers; from a Dutch newspaper-based lexical database [TROUW Corpus] for the clock times); logarithm of the morpheme frequency (i.e., cumulative frequency of all morphemes in the numeral; CELEX database [Baayen et al., 1995]). For example, the numeral 235 "tweehonderdvijfendertig" ["two-hundred five and thirty"] has two morphemes more than the numeral 230 "tweehonderddertig" ["two-hundred thirty"], namely the morphemes of "vijf" ["five"] and "en" ["and"].

We fitted a multilevel multiple regression model (Pinheiro & Bates, 2000; see also Lorch & Myers, 1990) to the data, with the logarithm of the naming latencies as the dependent variable and participant as the error stratum. In all the analyses reported in this article, we first entered the total set of variables as predictors and assessed which made a major contribution. From there, we constructed the best-fitting model. In regression analysis, it is important to check whether the dependent variable is roughly normally distributed (Chatterjee, Hadi, & Price, 2000), as with non-normality, the standard tests of significance may be invalidated. We therefore inspected the distribution of the naming latencies. Even after a logarithmic transformation to remove the skewing usually observed for reaction time distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest and longest naming latencies. Removal of individual data points with an RT lower than 300 ms or greater than 800 ms for the house number mode, and individual data points with an RT lower than 400 ms or greater than 1000 ms for the clock time mode led to a distribution that was approximately (log)normal.

The best-fitting regression model for the house number naming latencies included three predictor variables -- namely, the logarithm of the whole-form frequency[3], the logarithm of the morpheme frequency, and the numeral length

[3] The whole-form frequency counts for house numbers were taken from the CELEX database [Baayen et al., 1995]. To assess the robustness of this whole-form frequency effect, a new multilevel regression analysis was carried out, now using the house number frequency counts from TROUW corpus. In this corpus, two different frequency counts are listed: the frequency of the number name (i.e., the word TWEEHONDERD) and the frequency of the number itself (i.e., 200). A multilevel multiple regression model incorporating the TROUW whole-form

(i.e., the number of phonemes). We observed significant effects of all three predictors. A greater log morpheme frequency led to longer response latencies [$t(7766) = 2.72$, $p < .01$]. Longer numerals likewise elicited longer response latencies, [$t(7766) = 3.79$, $p < .001$]. In contrast, a greater log whole-form frequency led to shorter latencies, [$t(7766) = -2.38$, $p < 0.02$]. All effects remained significant in sequential analyses of variance -- that is, after partialing out the variance contributed by the other two variables ($p < .02$ for all analyses).

Furthermore, we observed three random effects: a main effect of participant (estimated standard deviation = 0.1311), an interaction of participant and trial number, indicating that the participants responded more quickly over trials (estimated standard deviation = 0.0004, log-likelihood ratio = 233.86, $p < .0001$), and an interaction of participant and number of phonemes (estimated standard deviation = 0.0024, log-likelihood ratio = 8.57, $p < .05$). In addition, the random effects were pairwise correlated: participant and trial (-0.46; i.e., the decrease of response latency in the course of the experiment was greater for slow participants than for fast participants), participant and number of phonemes (0.43; i.e., slow participants were especially slow when responding to longer numerals), and trial and number of phonemes (-0.76; i.e., participants who became faster during the experiment responded relatively slowly to longer numerals). The standard deviation of the residual error in the model was 0.154. The correlation between the observed and predicted naming latencies was .64, indicating a multiple R^2 of 42%.

Adding an extra group of predictor variables (i.e., the absolute magnitude of the whole number displayed and its logarithm or the absolute magnitude of the last two digits and its logarithm) did not significantly increase the amount of variance accounted for[4].

The multiple regression results suggest that for the production of a house number, the numeral length and frequency of the utterance are the major

frequency of the number name, but not the TROUW frequency of the number itself, explained the same amount of variance as the model incorporating the CELEX whole-form frequency.

[4] For naming house numbers, an alternative regression model can be constructed, which includes three predictor variables: 1) a factor coding for the hundreds versus the rest [e.g., 200 vs. 205, 210, etc.], 2) numeral length [number of phonemes], 3) logarithm of magnitude. However, in this model, the bèta-regression weight for (log)magnitude is rather low ($\beta = -0.0091$), indicating a very minimal contribution of magnitude. More importantly, this alternative model does not explain an equal amount of variance (although it contains the same number of factors) as the best-fitting, and therefore selected model reported in this paper.

determinants for speech production onset. As Figure 2 shows, a “zigzag” relation can be observed between utterance length and naming latencies for the number types from (10) to (55). The production of an additional number component (e.g., “three hundred twenty-*five*” in response to 325, compared with “three hundred twenty” in response to 320) is accompanied by an increase in naming latencies.

The same predictor variables as those used for the house number mode were also entered in a multiple regression analysis of the clock time naming latencies. In addition, we included another group of predictors pertaining to the conceptual preparation needed for clock time naming: (4) utterance referent (full hour, half hour, coming hour) and distance from referent (quarter/zero, five, ten minutes), with quarter/zero indicating a conceptually prominent distance. We again fitted a multilevel multiple regression model to the data, with the logarithm of the naming latencies as the dependent variable and participant as the error stratum.

The best-fitting regression model included the utterance referent, the distance from the referent, the logarithm of the morpheme frequency, and the logarithm of the whole-form frequency as predictor variables. We observed significant effects for all four predictors. Naming latencies differed depending on the utterance referent [$t(7863) = 31.27$, $p < .001$]. Furthermore, naming latencies varied depending on the distance from the referent [$t(7863) = 4.14$, $p < .001$]. A greater log morpheme frequency led to longer response latencies [$t(7863) = 6.92$, $p < .001$]. In contrast, a greater log whole-form frequency led to shorter latencies [$t(7863) = -3.57$, $p < .001$]. All effects remained significant after partialing out the variance contributed by the other three variables ($p < .01$ for all analyses).

The best-fitting model included two random effects: a main effect of participant (estimated standard deviation = 0.1559) and an interaction of participant and trial number, indicating that during the experiment the participants became faster (estimated standard deviation = 0.0004, log-likelihood ratio = 395.51, $p < .0001$). In addition, the random effects (participant and trial) were pairwise correlated (-0.63; i.e., the decrease of response latency in the course of the experiment was greater for the slow participants than for the fast participants). The standard deviation of the residual error in the model was 0.139. The correlation between the observed and the predicted naming latencies was .67, indicating a multiple R^2 of 44%. Adding an extra group of factors did not significantly increase the amount of variance accounted for.

These multiple regression results suggest that conceptual preparation is required for digital clock time naming. The differences in reference points (full hour, half hour, coming hour) were reflected in the naming latencies. Utterances referring to the full hour had a mean onset latency of 583 msec, utterances referring to the half hour took 673 msec to begin, and utterances referring to the coming hour took 643 msec to begin [$F_1(2, 58) = 69.3$, $p < .0001$; $F_2(2, 61) = 115.4$, $p < .0001$]. Furthermore, the differences in minutes were also reflected in the naming latencies. Utterances mentioning a 10-min distance took, on average, 654 msec to begin, utterances mentioning a 5-min distance took 632 msec, and utterances that mentioned a zero distance or a quarter took 594 msec to begin [$F_1(2, 58) = 74.2$, $p < .0001$; $F_2\ (2, 93) = 17.9$, $p < .0001$].

These findings support the idea of a procedural semantics (cf. Johnson-Laird, 1983) for clock time naming. In preparing a conceptual representation for a clock time on the basis of digital input, a speaker has to determine the reference hour and minutes. Let the input be *xyz* and assume that there is a procedure that, as a first step, determines the referent. If *yz* is smaller than 20, the reference hour is “x”; if it falls between 20 and 40, the reference hour is “half (x + 1)”; and if it is larger than 40, the reference hour is “x + 1” (cf. Bock, Irwin, Davidson, & Levelt, 2003; Meeuwissen, Roelofs, & Levelt, in press). If the specifications of the hour (“x”) and the coming hour (“x + 1”) are achieved by separate semantic procedures that take time, utterances referring to the full hour (“x”) should be produced more quickly than those referring to the coming hour (“x + 1”) and those referring to the half hour [“half (x + 1)”], as was empirically observed. The data suggest that, overall, specifying a 5-min distance takes less time than specifying a 10-min distance. However, the effect of the minutes (5 vs. 10) depends on the reference hour [full hour, half past the hour, next full hour; $F_1(2,58) = 4.79$, $p < .012$; $F_2(2, 58) = 3.03$, $p < .06$]. The latency difference between specifying 5 and 10 min is around 25 msec for the half hour and the coming hour, but it is only 5 msec for the full hour. This may be explained by the fact that whereas specifying the minutes relative to the half hour and coming hour requires a numerical transformation of the input (e.g., the 20 in 2:20 has to be transformed into “ten”, and the 25 in 2:25 into “five”), such a transformation is not required for the full hour (e.g., the 05 in

2:05 remains "five" and the 10 in 2:10 remains "ten"). In summary, the findings for the clock times support a procedural semantics in which hour and minute transformations are carried out.

DISCUSSION

To conclude, whereas the naming latencies in the house number mode were determined mostly by morphophonological factors, the clock time naming latencies revealed an additional conceptual involvement. Because response uncertainty was held constant, the data suggest that two naming routes exist. Which of the two routes is adopted in the naming of complex numerals appears to depend on the naming mode -- house number versus clock time. Importantly, canonically naming Arabic numerals (as house numbers) does not seem to require conceptual preparation, contrary to what Ferrand (1999) assumed.

EXPERIMENT 2

In the second experiment, the numerals of Experiment 1 were presented in an alphabetic format in both response modes. For example, instead of 215 and 2:15, the stimuli were now the Dutch equivalents of TWO HUNDRED FIFTEEN and QUARTER PAST TWO. According to our theory, conceptual transformations are now no longer necessary for clock time production. Consequently, morphophonological factors should determine the response latencies in both response modes.

METHOD

Participants

Twenty speakers, who did not participate in Experiment 1, took part in the experiment. They were undergraduate students at Nijmegen University and native speakers of Dutch and had normal or corrected-to-normal vision. They were paid for participation.

Materials

The same set of stimuli was used as that in Experiment 1, except that they were presented in an alphabetic format in both response modes. Again, the participants were instructed to start each response with the same word: *op* (at) for the house numbers and *om* (at) for the clock times.

Design and procedure

The design and procedure were identical to those in Experiment 1. Note that, although the speech output was identical to that in Experiment 1, by presenting stimuli in alphabetic format, the perceptual input now differs considerably between the two modes of response. More specifically, in Dutch, numbers are written as a connected string of letters (e.g., TWEEHONDERDVIJFENDERTIG; English, TWO HUNDRED THIRTY-FIVE), whereas clock times are conventionally divided by spaces (e.g., VIJF OVER HALF DRIE; in English, FIVE PAST HALF THREE). This difference might lead to a reduced discriminability of house numbers, as compared with clock times. Therefore, we decided to extend the presentation time for each stimulus up to 1,500 msec in order to make sure each stimulus was fully perceived. The following trial structure was used. First, the participant saw a warning signal (an asterisk) for 200 msec, directly followed by the display of a numeral for 1,500 msec. Stimuli were presented on a white background, printed in black. Before the next trial started, the screen went blank for another 500 msec. The total duration of the trial was 2.2 sec. The participants were instructed to read aloud the numerals as soon as they appeared on screen.

Analyses

A trial was considered invalid when it included a speech error, a voice key error, or a time-out or when a wrong oral response was given. Invalid trials were excluded from the statistical analyses. Furthermore, voice key errors and time-outs were excluded from the error analyses. Voice key errors and time-outs occurred in 1% and 0.3% of the trials in the house number mode and in 0.9% and 0.2% of the trials in the clock time mode, respectively.

RESULTS

Table 2 gives the mean reading latencies, standard deviations, and percentages of errors for the house number and clock time modes. Figure 3 shows the reading latencies for the 12 number types for the house number mode (upper panel) and the clock time mode (lower panel).

Table 2. *Mean Reading Latencies (in Milliseconds), Standard Deviations, and Percentages of Errors (E%) per Mode and Type for Experiment 2, With Reading of House Numbers and Clock Times Presented in Alphabetic Format.*

	Mode					
Type	House number			Clock time		
	M	*SD*	*E%*	*M*	*SD*	*E%*
00	493	125	1.9	480	115	0.4
05	507	128	0.8	507	137	1.3
10	513	131	3.1	508	132	1.0
15	510	138	2.9	507	133	2.3
20	505	138	2.7	524	130	3.5
25	521	141	3.3	532	137	3.5
30	501	122	1.7	482	113	1.0
35	527	136	3.8	534	141	1.7
40	503	127	2.1	529	140	1.0
45	519	133	5.8	502	124	2.9
50	498	136	1.7	515	129	3.1
55	511	131	5.2	511	135	2.5
Total	509	132	2.9	511	131	2.0

Errors

The participants made no more errors in the house number mode than in the clock time mode [$F_1(1, 19) = 1.34$, $p > .10$; $F_2(1, 84) = 10.90$, $p < .05$]. Errors varied depending on the number type [$F_1(11, 209) = 4.08$, $p < .0001$; $F_2(11, 84) = 3.83$, $p < .0001$]. The effect of number type did not vary with mode [$F_1(11, 209) = 1.32$, $p > .10$; $F_2(11, 84) = 2.25$, $p < .05$].

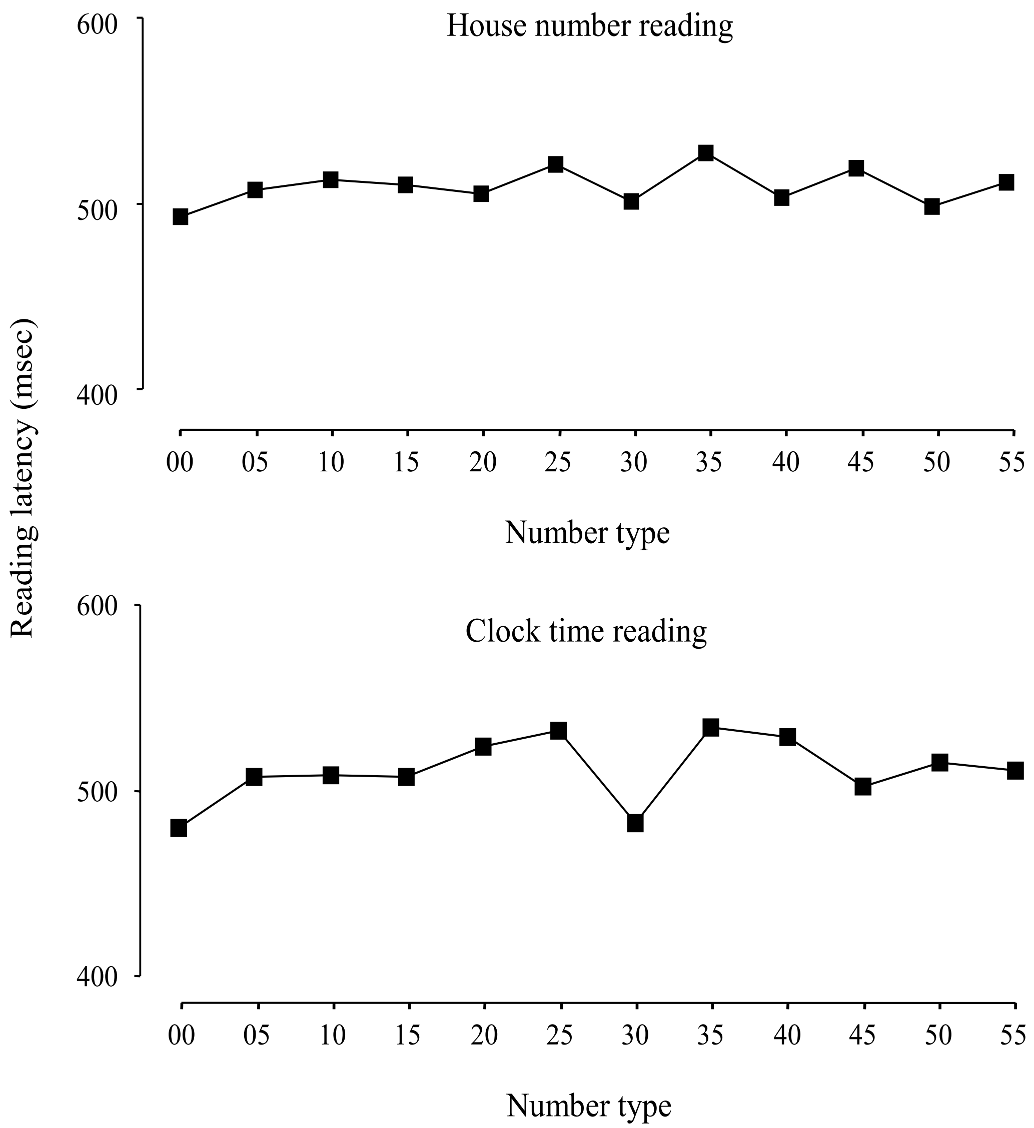

Figure 3. *Latencies, in milliseconds, for the reading of house numbers and clock times in alphabetic format in Experiment 2.*

Reading latencies

Reading latencies did not differ significantly between the two modes (both F_1 and $F_2 < 1$). However, number type had an effect [$F_1(11, 209) = 11.69$, $p < .0001$; $F_2(11, 84) = 16.71$, $p < .0001$]. Furthermore, the effect of number type depended on the mode [$F_1(11, 209) = 4.42$, $p < .0001$; F_2 $(11, 84) = 3.54$, $p < .0001$].

To gain further insight into the factors determining the reading latencies, we carried out multiple regression analyses, using the same factors as those in Experiment 1. We fitted multilevel regression models to the data, with the logarithm of the reading latencies as the dependent variable and participant as the error stratum. We inspected the distribution of the reading latencies. Even after a logarithmic transformation to remove the skewing usually observed for reaction time distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest reading latencies. Removal of individual data points with an RT lower than 300 ms for the house number mode, and individual data points with an RT lower than 400 ms for the clock time mode led to a distribution that was approximately (log)normal.

The best-fitting regression model for the house numbers included the number of morphemes as a predictor variable. We observed significant effects for the predictor in the model. Longer numerals, in terms of the number of morphemes, elicited longer reading latencies [$t(5312) = 7.25$, $p < .0001$].

The model included two random effects: a main effect of participant (estimated standard deviation = 0.1526) and an interaction of participant and trial number, indicating that the participants responded more quickly over trials (estimated standard deviation = 0.0004, log-likelihood ratio = 130.49, p < .0001). In addition, the random effects (participant and trial) were pairwise correlated (-0.54; i.e., the slower participants gained more speed during the experiment than did the faster participants). The standard deviation of the residual error in the model was 0.176. The correlation between the observed and the predicted reading latencies was .66, indicating a multiple R2 of 43%. Adding an extra group of factors did not significantly increase the amount of variance accounted for.

Thus, morphophonological factors determined the onset latencies in the reading of house numbers, as they did in the naming of the house numbers in

Experiment 1. However, whereas the number of phonemes affected the naming latencies in Experiment 1, they did not affect the reading latencies in the present experiment. Only the number of morphemes had an effect here.

To gain further insight into the factors determining the reading latencies for the clock time mode, we carried out multiple regression analyses, using the same factors as those in Experiment 1. Again, we fitted a multilevel regression model to the data, with logarithm of the reading latencies as the dependent variable and participant as the error stratum.

The best-fitting regression model included the number of morphemes as a predictor variable. We observed significant effects for the predictor in the model. Longer numerals, in terms of number of morphemes, elicited longer reading latencies [$t(4424) = 13.15$, $p < .0001$]. The model included two random effects: a main effect of participant (estimated standard deviation = 0.1136) and an interaction of participant and trial number, indicating that the participants responded more quickly over trials (estimated standard deviation = 0.0004, log-likelihood ratio = 129.24, $p < .0001$). In addition, the random effects (participant and trial) were pairwise correlated (-0.16; i.e., the slower participants gained more speed during the experiment than did the faster participants). The standard deviation of the residual error in the model was 0.145. The correlation between observed and predicted reading latencies was 0.66, indicating a multiple R^2 of 44%. Adding an extra factor did not significantly increase the amount of variance accounted for.

DISCUSSION

Thus, the manipulation of presentation format has been successful for the clock time mode. As was expected, the conceptual preparation found with an Arabic presentation format in Experiment 1 disappeared with the alphabetical presentation format in the present experiment.

To conclude, the number of morphemes was the sole major determinant of reading latencies in both response modes. This is in agreement with our theory, which presumes that a non-conceptual route suffices for the oral reading of numerals that are presented in an alphabetic format. Whereas the number of phonemes made a significant contribution in Experiment 1, it did not play a role here. We address this in the General Discussion section.

COMPARISON OF EXPERIMENTS 1 AND 2

Experiments 1 and 2 showed that the naming of house numbers takes less time than does the naming of clock times (457 vs. 626 msec), whereas the reading times for the house numbers and the clock times are comparable (509 vs. 511 msec). To compare the effects for the different modes (house number vs. clock time) between the naming task (Arabic format) and the reading task (alphabetic format), we carried out a joint analysis of variance with mode as within-subjects factor and task as between-subjects factor.

We observed a strong interaction between mode and task [$F_1(1, 48) = 66.57$, $p < .0001$; $F_2(1, 168) = 3721.85$, $p < .0001$], which corroborated our findings concerning the planning levels engaged by each task. The longer naming latencies for the clock times than for the house numbers in Experiment 1 can be explained by the additional conceptual operations required for the Arabic input in clock time naming. The finding that this latency difference disappeared for reading of the house numbers and clock times in Experiment 2 suggests that conceptual transformations were no longer necessary for successful reading task completion.

We also found a latency difference between the naming and reading of house numbers [457 msec and 509 msec, respectively; $t(22) = 14.5$, $p < .001$], despite the fact that the same spoken responses were required in the two tasks (e.g., the participants had to respond “tweehonderd” to both 200 and TWEEHONDERD). This result does not comply with Ferrand’s (1999) original finding of no latency difference between naming and reading. However, Ferrand used one-digit and two-digit Arabic numerals ranging from 1 to 20, for which the difference in orthographic length (i.e., the number of digits and letters) between the Arabic and alphabetic formats (e.g., 2 vs. TWO, etc.) was less than that in our study with three-digit Arabic numerals. The orthographic length was much smaller for the Arabic numerals in our Experiment 1 (all the numerals were three digits long; e.g., 235) than for the alphabetic numerals in Experiment 2 (e.g., TWEEHONDERDVIJFENDERTIG). The greater orthographic length for the alphabetic than for the Arabic format may have caused the difference in reading and naming times (i.e., longer times with greater orthographic length). In line with this account, a recent study by Pinel, Dehaene, Riviere, and LeBihan (2001) showed that identification of two-digit numerals is slower for the alphabetic than for the Arabic presentation format.

On first sight, the differential properties of the presentation formats seem unable to explain all the effects, because when one compares the clock time naming latencies obtained in Experiments 1 and 2, the latency difference goes in the opposite direction (511 msec for the alphabetic format, as compared with 626 msec for the Arabic format). However, given the evidence for conceptual preparation in Experiment 1, but not in Experiment 2, two opposing factors seem to play a role with clock times, making the latency difference difficult to interpret. In particular, the conceptual involvement with the Arabic numerals, but not with the alphabetic numerals, would increase the naming times relative to the reading times, whereas the greater orthographic length for the alphabetic numerals than for the Arabic numerals would increase the reading times relative to the naming times. The net result may be comparable to the latency for reading house numbers, which also involved reading alphabetic numerals without conceptual preparation, as was empirically observed (the reading times for the house numbers and clock times differed by 2 msec).

Importantly, despite the absolute difference in response latencies between naming and reading house numbers, it is striking that the same factors made a contribution, in the multiple regression analyses, for both presentation formats. As Figures 2 and 3 show, the experiments yielded a similar zigzag pattern for both presentation formats, following the overall length of the utterance to be planned (in terms of number of phonemes and morphemes). Such a pattern suggests that comparable planning processes are carried out in the naming and the reading of house numbers.

GENERAL DISCUSSION

On the basis of equal latencies for naming and reading numerals with equal response uncertainty, Ferrand (1999) argued that the naming of objects is slower than reading their names, due to a greater response uncertainty in naming than in reading, rather than to obligatory conceptual preparation for naming, but not for reading. We questioned the assumption that Arabic numerals have the same status as pictured objects. Instead, we advanced the view that Arabic numerals are processed like written words, and not like pictures. This view also is in accord with the absence of a latency difference between the naming of Arabic numerals and reading their names in alphabetic format when the visual complexity of the Arabic and the verbal numerals is matched (which seemed to hold for Ferrand, 1999, but not for our study), but this occurs for different reasons. More specifically, no conceptual preparation is needed for Arabic numerals in their canonical naming mode, such as in the naming of house numbers.

To test between the response uncertainty and conceptual preparation accounts, we manipulated the need for conceptual preparation while keeping response uncertainty constant in the naming and reading of complex numerals. In Experiment 1, the participants named three-digit Arabic numerals either as house numbers or as clock times. In line with our theory, the house number naming latencies were determined mostly by morphophonological factors, such as the number of phonemes, whereas the clock time naming latencies revealed additionally a strong conceptual involvement. In Experiment 2, the same numerals were presented in alphabetic format and had to be read aloud. The reading latencies for both house numbers and clock times were determined mostly by morphophonological factors. These results suggest that conceptual preparation, rather than response uncertainty, is responsible for the difference between naming and reading, at least in the case of numerals.

In Experiment 1, the number of phonemes and the morpheme and whole-form frequencies mainly determined the naming latencies in the house number mode. In contrast, in Experiment 2, the number of morphemes had a major influence. Note that the influence of morpheme frequency and the number of morphemes in reading suggests that the reading response was achieved lexically by retrieving morphemes, rather than through applying sublexical grapheme-phoneme correspondence rules. The difference between experiments may reflect a more conservative criterion for articulation initiation in naming than in reading (cf. Ferreira & Swets, 2002; Meyer, Roelofs, & Levelt, 2003). Information about the shape of the utterance (e.g., its length) is readily available from the visual input for reading numerals in alphabetic format, but not for naming them in Arabic format. If the utterance is planned out morphologically for both reading and naming but more is planned at the phonological level for naming than reading (e.g., the first phonological word for reading, but more than the first phonological word for naming), the effect of number of morphemes and phonemes may differ between naming and reading. More extensive planning at the phonological level may mean that the influence of the number of phonemes increases relative to the influence of number of morphemes. This may explain why, in the naming of house numbers (Experiment 1), the number of phonemes had an influence but the number of morphemes did not. It also explains why, for reading (Experiment 2), the opposite pattern holds -- namely, that the number of morphemes had an influence but the number of phonemes did not. Whatever the exact reason may be for the difference in influence of form-level factors between Experiments 1 and 2, most important is that form-level factors mainly determined the reading response in both modes in Experiment 2 and the naming of house numbers in Experiment 1, in contrast to the strong conceptual involvement observed for the naming of digital clock times in Experiment 1.

The absence of evidence for conceptual preparation in the reading of house numbers and clock times in alphabetic format might seem to be at odds with the recent literature on reading, where effects of semantic factors have been reported (e.g., Strain, Patterson, & Seidenberg, 1995). Note, however, that whereas studies of the reading of isolated words have typically investigated the reading of monosyllabic, monomorphemic words, the present experiments examined the reading of polysyllabic, polymorphemic numerals. It cannot be excluded that different types of words vary in the involvement of meaning in reading aloud. Moreover, most reading models (e.g., Coltheart et al., 2001; Plaut et al., 1996) assume both conceptual and nonconceptual routes for reading aloud, supported by studies that suggest that conceptual preparation is not essential for reading simple words. For example, the acquired dyslexic patient W.L.P. reported by Schwartz, Saffran, and Marin (1980) could read aloud words (including words with irregular spellings) that she did not understand. Moreover, semantic effects are not observed in all reading tasks. In particular, whereas the effects are obtained in the lexical decision task, they are typically absent in reading aloud. In reviewing the literature, Shibahara, Zorzi, Hill, Wydell, and Butterworth (2003) suggested that, so far, only imageability has been shown to have an effect on reading latencies (e.g., Strain et al., 1995). However, imageability seems low in the case of complex numerals, so an effect of this factor was not to be expected in our experiments. Instead, the semantic factor typically affecting responding to numerals is magnitude.

In our experiments, the magnitude of the whole three-digit numeral and of its last two digits did not make a significant contribution to the latencies for responding to house numbers in either presentation format (Arabic and alphabetic). Although an overall increase in naming latencies can be observed in Experiment 1 (see Figure 2), both the multiple regression results and the specific shape of the latency pattern do not support a magnitude account of the data. If magnitude had played a role in the naming and reading of house numbers, we should have seen a steady increase in latencies from number type (00) to (55) and not the observed zigzag pattern -- that is, the increase in latency from numerals endings with 5 (the longer numerals), as compared with those ending with 0 (the shorter ones). It should be noted that whereas magnitude effects have been reported for numerals up to 99 (Brysbaert, 1995), in the present study, more complex, three-digit numerals were investigated. Moreover, magnitude effects are typically observed in tasks in which Arabic numerals have to be manipulated or compared quantitatively (Dehaene, 1992; Fias, 2001), whereas in our experiments the numerals had to be named or read. Our results suggest that the naming and reading of house numbers requires no conceptual preparation, whereas the naming of digital clocks does, which suggests that conceptual preparation depends on the exact task and materials used (cf. Cipolotti & Butterworth, 1995).

To conclude, our study suggests that naming complex Arabic numerals canonically as house numbers does not obligatorily engage conceptual preparation, whereas naming them as clock times does. This means that the equal latencies for canonically naming Arabic numerals and reading their names (observed by Ferrand, 1999) cannot be taken as evidence for a response uncertainty account of the difference between object naming and reading their names. Instead, the present study suggests that, paralleling the difference between naming Arabic numerals as clock times and house numbers, obligatory conceptual preparation for object naming, but not for reading their names is a crucial factor.

TRACKING THE EYES IN NAMING AND READING COMPLEX NUMERALS FOR TIME AND SPACE

CHAPTER 3

Marjolein Meeuwissen, Ardi Roelofs, and Willem J. M. Levelt[1]

ABSTRACT

Two eye-tracking experiments are reported that examined gaze durations and response latencies in planning the production of complex spoken numerals for time and space. Complex numeral pairs were named (Arabic format, Experiment 1) or read aloud (alphabetic format, Experiment 2) as house numbers and as clock times. Gaze durations for naming and reading house numbers and clock times were determined by morphophonological variables. In addition, gaze durations for naming but not for reading clock times reflected an influence of conceptual variables. The same variables determined naming and reading latencies for clock times. However, none of the variables determined the naming and reading latencies for house numbers, indicating a dissociation between response latencies and gaze durations. Moreover, numeral length determined the gaze durations but not the response latencies for clock times. These results suggest that speakers adopt different criteria for articulation onset and shift of gaze for long utterances, both in naming and oral reading.

[1] An adapted version of this chapter is under revision for publication.

INTRODUCTION

Previous studies of object naming have suggested that there is a tight link between eye movements and speech planning processes (e.g., Griffin & Bock, 2000). In particular, gaze durations in object naming have been shown to depend on the time to plan the sound of the corresponding name (Meyer, Sleiderink, & Levelt, 1998; Griffin, 2001). For example, when speakers have to first name a left object and then a right object, they look longer at left objects with two- than with one-syllable names even when the object recognition times are the same (Meyer, Roelofs, & Levelt, 2003). Furthermore, speakers look longer at objects with low frequency than with high frequency names (Griffin, 2001; Meyer et al., 1998). Moreover, Meyer and Van der Meulen (2000) observed that both response latencies and gaze durations in object naming are affected by auditory primes. Speakers were presented with object pairs together with auditory prime words, which could be either phonologically related or unrelated to the name of the left object. Both response latencies and gaze durations for left objects were shorter with related than with unrelated auditory primes. This held regardless of whether the auditory words primed the first or the second syllable of the object name. The effects of word length, frequency, and phonological priming suggest that the shift of gaze from the left to the right object is initiated only after the sound form of the name for the left object has been planned.

The earlier eye-tracking studies showed that gaze durations reflect the manipulation of binary variables, such as one- versus two-syllable names (Meyer et al., 2003), high- versus low-frequency names (Griffin, 2001; Meyer et al., 1998), and primed versus unprimed syllables (Meyer & Van der Meulen, 2000). It is unclear, however, whether gaze durations are also sensitive to the broader range of variables that determine speech planning latencies. Eye-tracking research of reading for comprehension, for example, has shown that gaze durations in reading reflect a host of variables, such as graded effects of word length, word frequency, and contextual constraint (Rayner, 1998). The question that is addressed in the current paper is whether this also holds for naming and oral reading. To examine this, we investigated the naming and reading of complex numerals for time and space, in particular, the naming and reading aloud of clock times (time) and house numbers (space).

Earlier research on complex spoken numeral production in Dutch has provided evidence about the variables that determine the naming and reading latencies of house numbers and clock times between 200 and 955 and 2:00 and 9:55 (all numerals ending on 0 or 5), respectively. Meeuwissen, Roelofs, and Levelt (2003) obtained evidence that similar speech planning processes are involved in naming house numbers from Arabic digit format (e.g., 235) and reading them aloud from alphabetic format (e.g., Dutch TWEEHONDERDVIJFENDERTIG). For both naming and reading alike, response latencies were determined by morphophonological factors, such as the number of phonemes and morphemes, and the log morpheme and whole-form frequencies. For clock time naming (i.e., Arabic format), response latencies not only demonstrated the influence of morphophonological factors, but also of conceptual factors, reflecting the conceptual operations required in telling time in the Dutch language. In Dutch, time is told in a relative way, with time expressions not only making reference to the full hour like in English, but also to the half hour (see Bock, Irwin, Davidson, & Levelt, 2003). This secondary referent in Dutch applies between ten minutes before and ten minutes after the half hour, yielding for example "tien voor half drie" (literally "ten before half three") for 2:20. To tell time from a digital clock in Dutch, the digits in the input have to be used to determine the utterance referent and the distance in minutes from that referent. These conceptual operations were reflected in the naming latencies of the clock times (Meeuwissen et al., 2003, in press). When the conceptual operations were made unnecessary by presenting the clock times in alphabetic format, the response latencies were only determined by morphophonological factors, just as they were in reading the house numbers.

The experiments by Meeuwissen et al. (2003, in press) measured naming and reading latencies but not gaze durations. Other studies on numeral naming recorded gaze durations but not naming latencies. Pynte (1974) measured eye movements during the silent naming of two-digit Arabic numerals and observed that gaze durations increased with the number of syllables in the numeral names. Pynte's stimuli differed not only in number of syllables but also in number magnitude and numeral frequency. In order to determine the contribution of all three factors, Gielen, Brysbaert, and Dhondt (1991) conducted multiple regression analyses on the gaze durations in the silent naming of all one- and two-digit

Arabic numerals ranging from 0 to 99. The regressions indicated that the number of syllables and the numeral frequency, but not the number magnitude determined the gaze durations, even when the contribution of the other factors was partialed out. Because Pynte (1974) and Gielen et al. (1991) asked for silent naming, their studies did not provide evidence about the corresponding naming latencies and the relation between naming latencies and gaze durations. However, gaze durations and naming latencies do not always point in the same direction, as shown by Levelt and Meyer (2000).

Levelt and Meyer (2000) reported that response latencies and gaze durations can dissociate in that gaze durations may reflect the phonological length (e.g., number of syllables) of the utterance even when response latencies do not. In their study, speakers were instructed to describe colored left and right objects (e.g., a big red scooter and a ball) in a simple or a complex way. Participants either had to respond with “the scooter and the ball” or “the *big red* scooter and the ball”. Gaze durations for the left object (the scooter) were much shorter for the simple utterances (559 ms) than for the complex utterances (1229 ms). However, speech onset latencies did not differ between the two utterance types. Furthermore, the shift of gaze to the right object was initiated before speech onset for the simple utterances, but after speech onset for the complex utterances. This suggests that the shift of gaze, but not the onset of articulation, is triggered by the completion of phonological encoding of the first object name. It seems that speakers may adopt different criteria for the onset of articulation and a shift of gaze in multiple object naming.

Below, we report two experiments that examined the naming and oral reading of complex numerals pairs by measuring both response latencies and gaze durations. The aim was to examine whether gaze durations reflect the speech planning levels (from conceptual to morphophonological encoding) that are involved in the naming and reading of complex numerals for time and space, as observed by Meeuwissen et al. (2003). Furthermore, we were interested in whether graded effects of number of segments, frequency, and so forth, are reflected in gaze durations for naming and oral reading. In Experiment 1, Dutch speakers named complex numeral pairs presented in Arabic digit format as house numbers and as clock times. For example, when presented with 300 and 505, participants responded with “op driehonderd en vijfhonderdvijf” (literally “at three hundred and five hundred five") and when presented with 3:00 and 5:05, they said "om drie uur en vijf over vijf" (literally "at three o'clock and five past five"). In Experiment 2, the same numeral pairs were presented in alphabetic format and they had to be read aloud.

We expected to find the same pattern of results for the gaze durations as we previously found for response latencies (Meeuwissen et al., 2003), assuming that a shift of gaze from the left to the right numeral is initiated only after sufficient speech planning for the left numeral has been completed. Specifically, for naming and reading aloud house numbers, we expected gaze durations to depend on morphophonological factors. Furthermore, we expected gaze durations for reading clock times to depend on morphophonological factors and the gaze durations for naming clock times to depend on both morphophonological and conceptual factors. Moreover, given the findings of Levelt and Meyer (2000), it is important to assess whether a dissociation occurs between gaze durations and response latencies, and if so, whether comparable dissociations are obtained for naming (Arabic format) and reading (alphabetic format).

EXPERIMENT 1

In the first experiment, speakers named complex numeral pairs presented in Arabic digit format as house numbers or as clock times. We measured gaze durations and naming latencies for the first numeral. Do the gaze durations mirror the naming latency results found earlier (Meeuwissen et al., 2003), with morphophonological factors determining the naming of house numbers, and both morphophonological and conceptual factors determining the naming of clock times? Moreover, is a dissociation obtained between naming latencies and gaze durations in that gaze durations reflect the morphophonological and conceptual factors even when naming latencies do not?

METHOD

Participants

Twenty native speakers of Dutch participated in the experiment. They were undergraduate students of Nijmegen University. They had normal or corrected-to-normal vision. They were paid for their participation.

Materials and Design

Stimuli consisted of 3-digit Arabic numerals ranging from 200 to 955 ending either on 0 or 5. This yielded 12 different number types collapsed across the hundreds and the hours: (00) 200, 300, … (05) 205, 305, … (10) 210, 310, … (15) 215, 315, … (20) 220, 320, … (25) 225, 325, … (30) 230, 330, … (35) 235, 335, … (40) 240, 340, … (45) 245, 345, … (50) 250, 350, … (55) 255, 355, … For each type, there were 8 instances (e.g., for type (00), the instances were 200, 300, 400, 500, 600, 700, 800, and 900). Note that numbers ranging from 100 to 155 were excluded from the stimulus set. For numbers in the interval of 100 to 199, in Dutch no explicit information is encoded about the particular hundred involved. For instance, in Dutch the number 105 is pronounced as "honderdvijf" (literally "hundred five"), whereas the number 205 is pronounced as "*twee*honderdvijf" (literally "*two* hundred five").

Each numeral was paired with three different other numerals. A particular pair of numerals occurred only once in the whole experiment (i.e., irrespective of the left- or right-hand position of the stimuli), and each left-hand numeral was paired with numerals that belonged to a different group of hundreds (e.g., 200 and 305 together, but not 200 and 245). Numerals were scaled to fit into a virtual frame of 8.18 by 7.45 cm, corresponding to visual angles of 7.1^{o} horizontally and 6.5^{o} vertically when viewed from the participant's position, approximately 65 cm away from the screen. The distance between the midpoints of these virtual frames was 14.97 cm (13^{o}).

Each mode of response (house number, clock time) was tested in a separate block of trials. The order of presenting the numeral pairs was random. The order of testing each response mode was counterbalanced across participants.

Apparatus

A Compaq 486 computer controlled the experiment. Materials were presented on a ViewSonic 17PS screen. Eye movements were measured using an SMI EyeLink-Hispeed 2D head-mounted eye tracking system (SensoMotoric Instruments GmbH, Teltow, Germany). The position of the right eye was determined every 4 ms. The spatial accuracy of the eye tracker is better than 0.1^{o}. The participants' speech was recorded using a Sennheiser ME400 microphone and a SONY DTC55 DAT recorder. Response latencies were measured using a voice key.

Procedure

The participants were tested individually. They were told that they would see pairs of 3-digit numerals, which they should name in noun phrases either as house numbers or as clock times, with the conjuntion *en* ("and") between the numerals. Each response had to start with the same word: *op* (literally: "at") for the house number mode and *om* (literally: "at") for the clock time mode. In this way, all responses started with the same phoneme.

The headband of the eye-tracking system was placed on the participant's head and the system was calibrated. For calibration, a grid of three by three positions had been defined. During a calibration trial, a fixation target appeared once, in random order, in each of these positions for one second. Participants were asked to fixate upon each target until the next target appeared. After the calibration trial, the estimated positions of the participant's fixations and the distances from the fixation targets were displayed to the experimenter. Calibration was considered adequate if there was at least one fixation within 1.5^{o} of each fixation target. When calibration was inadequate, the procedure was repeated, sometimes after adjusting the eye cameras. Successful calibration was followed by a validation trial. For the participants, this trial did not differ from the calibration trial, but the data collected during the validation trial were used to estimate the participants' gaze positions, and the error (i.e., the distance between the estimated gaze position and the target position) was measured. Validation was considered completed if the average error was below one degree and the worst error below 1.5 degrees. Depending on the result of the validation trial, the calibration and validation trials were repeated or testing began. Calibration was repeated before the experiment and during the breaks.

A fixation point appeared in the center of the frame for the left-hand numeral for 850 ms at the beginning of each test trial. Previous studies by Meyer et al. (1998, 2003) showed that participants have a strong tendency to inspect and name the left stimulus first, which was reinforced here by the presentation of the fixation point. Next, the numeral pair was presented and remained on the screen until the participant had fully completed the task and pushed a button for the next trial. After every 48 trials there was a short break.

Analyses

A trial was considered invalid when it included a speech error, when a wrong oral response was produced, or when the voice key was triggered incorrectly. Error trials were discarded from the analyses of gaze durations and response latencies. To analyze the speakers' gaze durations, we first classified their eye fixations as falling on the left or right numeral or elsewhere. A fixation was counted as on a numeral if its coordinates lay within or on the outer contours of the numeral. Furthermore, trials on which speakers did not fixate on the left numeral first before turning to the right numeral were excluded from analyses (less than 1 % of all cases). The first-pass gaze duration was defined as the time interval between the beginning of the first fixation on the left-hand numeral and the end of the last fixation before the first shift of gaze is initiated to the right-hand numeral.

The naming latencies, gaze durations, and errors were submitted to by-participant (F_1) and by-item (F_2) analyses of variance with the crossed variables mode and type. Interactions of mode and type were further explored through multi-level multiple regressions on the total data set.

RESULTS

Table 1 gives the mean naming latencies, their standard deviations, the first-pass gaze durations, their standard deviations, and the error percentages for the twelve numeral types in the house number and clock time modes. Figure 1 displays the mean gaze durations and naming latencies for the house numbers (upper panel) and clock times (lower panel).

Table 1. *Mean Latencies for the Vocal Responses (M, in Milliseconds) and their Standard Deviations (SD), Gaze Shifts (M, in Milliseconds) and their Standard Deviations (SD), and Error Percentages (E%) per Mode and Type for Experiment 1.*

	Mode									
Type	House number					Clock time				
	Vocal		Gaze			Vocal		Gaze		
	M	SD	M	SD	E%	M	SD	M	SD	E%
00	545	190	749	332	3.3	615	195	633	212	5.6
05	545	206	925	326	4.0	641	212	967	324	7.3
10	551	196	889	322	3.7	660	213	919	311	5.6
15	549	201	1007	336	5.2	660	212	952	307	8.1
20	553	197	976	334	3.5	742	269	1322	453	7.7
25	549	191	1172	364	5.2	726	252	1300	432	7.1
30	551	197	960	340	5.4	703	249	920	310	8.8
35	555	208	1227	384	6.5	702	249	1367	416	6.3
40	556	203	1001	365	5.8	731	246	1375	457	8.5
45	562	208	1274	397	5.6	700	231	997	361	7.5
50	558	214	1023	476	3.3	722	274	1111	434	9.0
55	564	208	1245	387	4.2	679	253	1051	357	7.7
Total	553	202	1037	397	4.7	689	241	1076	430	7.4

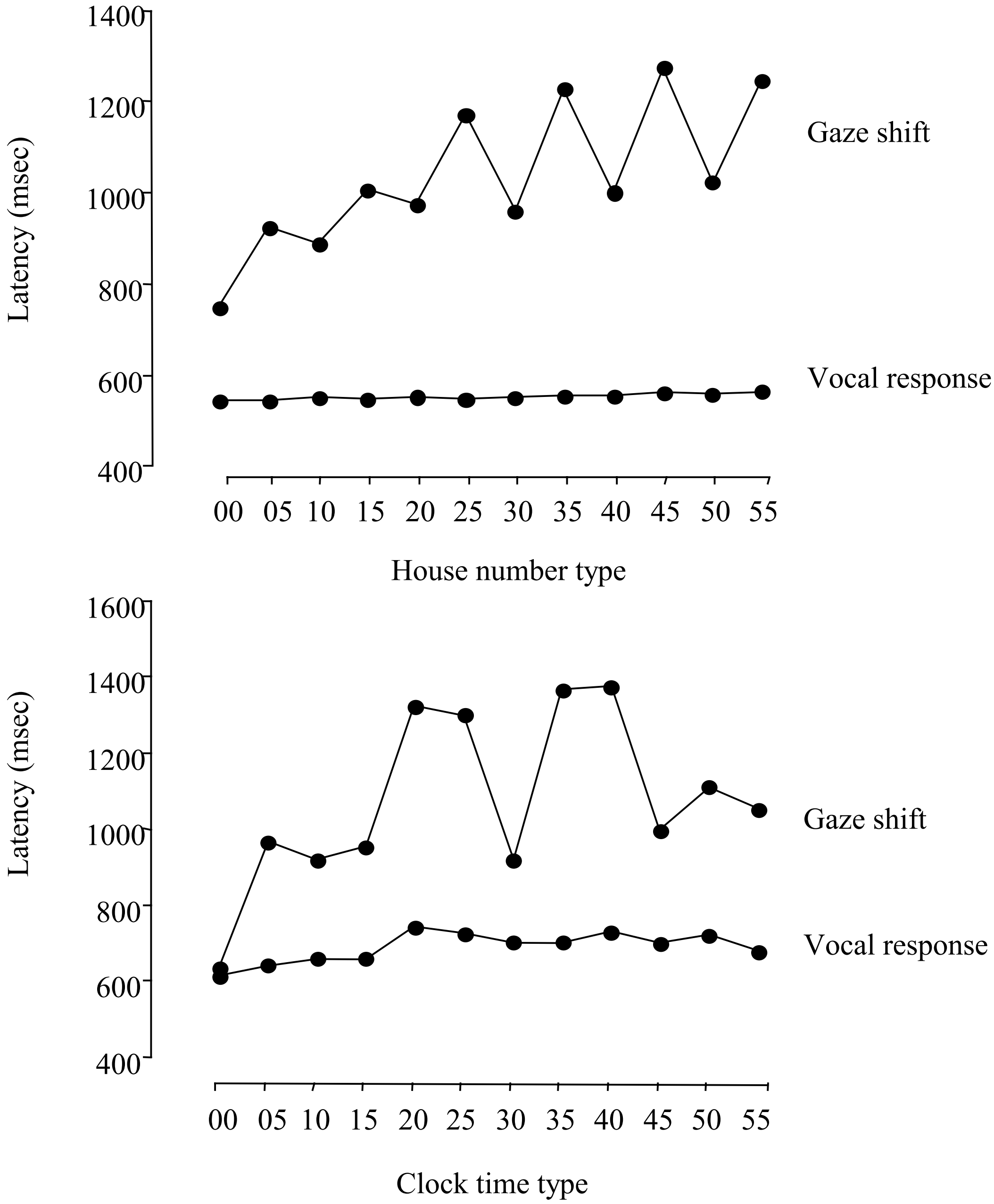

Figure 1. *Mean latencies of the vocal response and the shift of gaze in naming house numbers and clock times in Experiment 1.*

Errors

Participants made fewer errors in the house number mode than in the clock time mode [$F_1(1, 19) = 33.38$, $p < .001$; $F_2(1, 84) = 28.31$, $p < .001$]. As indicated by Table 1, most errors were made in the slowest condition, so there is no evidence for a speed-accuracy tradeoff. There were no other significant effects.

Naming latencies

Naming latencies were on average 136 milliseconds shorter for the house numbers than for the clock times [$F_1(1, 19) = 27.31$, $p < .001$; $F_2(1, 84) = 983.16$, $p < .001$]. Moreover, naming latencies depended on type [$F_1(11, 209) = 8.03$, $p < .001$; $F_2(11, 84) = 11.22$, $p < .001$]. Furthermore, the effect of type varied with mode [$F_1(11, 209) = 7.74$, $p < .001$; $F_2(11, 84) = 5.93$, $p < .001$].

To gain further insight in the factors underlying the interaction between type and mode, we ran multiple regression analyses over the total data set following Meeuwissen et al. (2003). The predictor variables concerned either conceptual or morphophonological factors involved in speech planning. The following groups of predictor variables were entered into the analyses (identical to Meeuwissen et al., 2003) for conceptual level planning: (1) magnitude for house numbers: absolute magnitude of the whole 3-digit number and its logarithm, and (2) clock concepts for clock times: utterance referent (full hour, half hour, coming hour) and distance from referent (zero, five, ten, or fifteen minutes).

Furthermore, the following groups of predictor variables, pertaining to morphophonological planning, were included for both house numbers and clock times: (1) numeral length: number of morphemes; number of syllables; number of phonemes, and (2) frequency: logarithm of the whole-form frequency; logarithm of the morpheme frequency (i.e., cumulative frequency of all morphemes in the numeral).

We fitted a multi-level multiple regression model (Pinheiro & Bates, 2000; see also Lorch & Myers, 1990) to the data with the logarithm of naming latencies as dependent variable and participant as error stratum. In all analyses reported in this paper, we first entered the total set of variables as predictors and assessed which made a major contribution. From there, we constructed the best-fitting model. In regression analysis, it is important to check whether the dependent variable is roughly normally distributed (Chatterjee, Hadi, & Price, 2000), as with non-normality, the standard tests of significance may be invalidated. We therefore inspected the distribution of the naming latencies. Even after a logarithmic transformation to remove the skewing usually observed for reaction time distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest and longest naming latencies. Removal of individual data points with an RT lower than 400 ms or greater than 2000 ms for both response modes led to a distribution that was approximately (log) normal.

For the house numbers, none of the above mentioned factors made a significant contribution in the regression analysis. As shown by the upper panel of Figure 1, naming latencies for the twelve number types were fairly constant, despite considerable differences in numeral length.

For the clock times, the best-fitting regression model included the utterance referent, distance from the referent, and the logarithm of morpheme frequency as predictor variables.

We observed significant effects for all three predictors. Naming latencies differed depending on the utterance referent [$t(4784) = 15.75$, $p < .001$]. As shown by the lower panel of Figure 1, utterances referring to the full hour (i.e., 00, 05, 10, 15) were produced much faster than utterances referring to the half hour (i.e., 20, 25, 30, 35, 40) and the coming hour (i.e., 45, 50, 55). Furthermore, naming latencies varied depending on the distance in minutes from the referent [$t(4784) = 2.96$, $p < .01$]. Figure 1 shows that clock times mentioning a greater distance from the referent (e.g., ten minutes) resulted in longer response latencies than smaller distances from the referent (e.g., five minutes). A greater log morpheme frequency led to longer naming latencies [$t(4784) = 4.26$, $p < .0001$]. All effects remained significant after partialing out the variance contributed by the other variables ($p < .01$ for all analyses).

Furthermore, the best-fitting model included two random effects: participant (estimated standard deviation = 0.1818) and an interaction of participant and trial number, indicating that during the experiment participants became faster (estimated standard deviation = 0.0004, log-likelihood ratio = 77.87, $p < .0001$). In addition, the random effects were pairwise correlated: participant and trial (-0.19; i.e., the decrease of naming latency in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.202. The correlation between the observed and the predicted naming latencies was 0.66, indicating a multiple R^2 of 44 %. Adding an additional group of factors did not significantly increase the amount of variance accounted for. To summarize, the multiple regression results for the naming latencies suggest that conceptual preparation is needed for naming clock times presented in Arabic digit format, which replicates earlier findings (Meeuwissen et al., 2003).

Gaze durations

Gaze durations were on average 39 milliseconds shorter for the house numbers than for the clock times [$F_1(1, 19) = .38$, $p < 1$; $F_2(1, 11) = 41.06$, $p < .001$]. Moreover, gaze durations depended on type [$F_1(11, 209) = 150.80$, $p < .001$; $F_2(11, 84) = 191.69$, $p < .001$]. Furthermore, the effect of type varied with mode [$F_1(11, 209) = 54.23$, $p < .001$; $F_2(11, 84) = 86.08$, $p < .001$].

To gain further insight in the factors underlying the interaction between type and mode, we ran multiple regression analyses over the total data set. The same predictor variables used for the analysis of naming latencies were also entered in the multiple regression analysis of the gaze durations. We inspected the distribution of the gaze durations. Even after a logarithmic transformation to remove the skewing usually observed for gaze duration distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest and longest gaze durations. Removal of individual data points with a GD lower than 400 ms or greater than 2000 ms for the house number mode, and individual data points with a GD lower than 300 ms or greater than 2000 ms for the clock time mode led to a distribution that was approximately (log) normal.

The best-fitting regression model for the house number gaze durations included three predictor variables, namely the logarithm of the whole-form frequency, the logarithm of the morpheme frequency, and numeral length (i.e., the number of morphemes and phonemes). We observed significant effects of all three predictors. A greater log whole-form frequency led to shorter gaze durations [$t(5398) = -4.59$, $p < .0001$]. A greater log morpheme frequency likewise led to shorter gaze durations [$t(5398) = -3.01$, $p < .01$]. In contrast, longer numerals elicited longer gaze durations [$t(5398) = 13.84$, $p < .0001$] for the number of morphemes, and for the number of phonemes [$t(5398) = 9.53$, $p < .0001$].

As shown by the upper panel of Figure 1, gaze durations varied quite consistently with numeral length. House number utterances mentioning an additional morpheme (e.g., house numbers ending on a 5, like 235 requiring the response "tweehonderd*vijfen*dertig") were looked at much longer than shorter utterances (e.g., house numbers ending on a 0, like 230 requiring the response "tweehonderddertig"). All effects remained significant in sequential analyses of variance, that is, after partialing out the variance contributed by the other two variables ($p < .0001$ for all analyses). Furthermore, we observed two random effects: participant (estimated standard deviation = 0.2325), and an interaction of participant and trial number, indicating that gaze durations became shorter over trials (estimated standard deviation = 0.0005, log-likelihood ratio = 324.62, $p < .0001$). In addition, the random effects were pairwise correlated: participant and trial (-0.27; i.e., the decrease of gaze duration in the course of the experiment was greater for slow participants than for fast participants). The standard deviation of the residual error in the model was 0.202. The correlation between the observed and predicted gaze durations was 0.77, indicating a multiple R^2 of 59%. Adding an additional group of factors did not significantly increase the amount of variance accounted for.

These multiple regression results suggest that when pairs of house numbers have to be named, gaze durations for the left-hand house number are determined by morphophonological factors such as the whole-form and morpheme frequencies and numeral length (i.e., the number of phonemes and morphemes). These findings for gaze durations replicate earlier findings on the latencies of naming single three-digit house numbers (Meeuwissen et al., 2003). Also, they replicate the evidence obtained by Pynte (1974) about the effect of numeral length on gaze durations in the silent naming of two-digit numerals and the evidence on the effect of numeral length and frequency on gaze durations in the silent naming of one- and two-digit numerals obtained by Gielen (1991).

The best-fitting regression model for the clock time gaze durations included four predictor variables, namely utterance referent, distance from the referent, logarithm of whole-form frequency, and numeral length (i.e., the number of morphemes). We observed significant effects of all four predictors. Gaze durations differed depending on the utterance referent [$t(5487) = 24.93$, $p < .0001$]. As shown by the lower panel of Figure 1, utterances referring to the full hour were looked at much shorter than utterances referring to the half hour or the coming hour. Furthermore, gaze durations varied depending on the distance from the referent [$t(5487) = 6.58$, $p < .05$]. Figure 1 shows that utterances mentioning a greater distance from the referent were looked at much longer than utterances mentioning a smaller distance. A greater log whole-form frequency led to shorter gaze durations [$t(5487) = -14.23$, $p < .0001$]. Longer clock time utterances (i.e., in terms of number of morphemes) elicited longer gaze durations [$t(5487) = 12.20$, $p < .0001$]. All effects remained significant after partialing out the variance contributed by the other three variables ($p < .0001$ for all analyses).

Furthermore, the best-fitting model included two random effects: participant (estimated standard deviation = 0.1941), and an interaction of participant and trial number (estimated standard deviation = 0.0005, log-likelihood ratio = 223.75, p < .0001), indicating that gaze durations became shorter over trials. In addition, the random effects (participant and trial) were pairwise correlated (-0.28; i.e., the decrease in gaze duration in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.22. The correlation between the observed and the predicted gaze durations was 0.75, indicating a multiple R^2 of 56 %. Adding an additional group of factors did not significantly increase the amount of variance accounted for. To summarize, the multiple regression results showed that when pairs of clock times have to be named, the gaze durations for the left-hand clock time are determined by both conceptual and morphophonological factors. This replicates earlier findings for naming latencies (Meeuwissen et al., 2003).

DISCUSSION

The gaze durations but not the response latencies for the numeral pairs replicate the earlier findings on the response latencies for single numerals (Meeuwissen et al., 2003). The multiple regression results for the house numbers revealed a dissociation between naming latencies and gaze durations, with naming latencies being constant and gaze durations reflecting the influence of morphophonological variables. In contrast, naming latencies and gaze durations for the clock times point in the same direction. Both reflect the influence of conceptual and morphophonological variables. However, numeral length determined the gaze durations but not the response latencies for both the house numbers and the clock times. We provide an explanation of these dissociations between gaze durations and response latencies in the General Discussion section.

EXPERIMENT 2

In the second experiment, the complex numeral pairs of Experiment 1 were presented in alphabetic format. Participants read the numerals aloud as house numbers or as clock times. For example, they said "op tweehonderd en driehonderdvijf" (literally "at two hundred and three hundred five") in response to the pair TWEEHONDERD and DRIEHONDERDVIJF, and they said "om twee uur en vijf over drie" (literally "at two o'clock and five past three") in response to the pair TWEE UUR and VIJF OVER DRIE. We measured gaze durations and reading latencies for the first alphabetic numeral of a pair. Do the gaze durations mirror the reading latency results found earlier (Meeuwissen, 2003), with only morphophonological factors determining the reading of house numbers and clock times? Moreover, is a dissociation obtained between reading latencies and gaze durations in that gaze durations reflect the morphophonological factors even when reading latencies do not?

METHOD

Participants

Thirty native speakers of Dutch, who did not participate in Experiment 1, took part in the experiment. They were undergraduate students of Nijmegen University. They were paid for their participation.

Materials, Apparatus, Design, and Procedure

This was identical to Experiment 1, except that numerals were now presented in alphabetic format for both response modes. By presenting numerals in alphabetic format, the perceptual input differed considerably between the two response modes. In Dutch, house numbers are conventionally written as a connected string of letters, such as TWEEHONDERDVIJFENDERTIG, which no longer enabled a pair of house numbers to be presented horizontally on the computer screen. Therefore, we presented the alphabetic numerals in the upper and lower half of the screen.

Analyses

A trial was considered invalid when it included a speech error, when a wrong oral response was produced, or when the voice key was triggered incorrectly. Error trials were discarded from the analyses of the gaze durations and reading latencies. To analyze the speakers' gaze durations, we first classified their eye fixations as being located on the upper or lower alphabetic numeral or elsewhere. A fixation was counted as being located on an alphabetic numeral if its coordinates lay within or on the outer contours of the numeral. On most trials, participants first fixated the upper and then the lower alphabetic numeral. Trials on which this was not the case were excluded from the analysis of the gaze durations and response latencies (this held for less than 1% of all trials).

The reading latencies, gaze durations, and errors were submitted to by-participant (F_1) and by-item (F_2) analyses of variance with the crossed variables mode and type. Interactions of mode and type were further explored through multi-level multiple regressions on the total data set.

RESULTS

Table 2 gives the mean reading latencies, their standard deviations, the first-pass gaze durations, their standard deviations, and the error percentages for the numeral types in the house number and clock time modes. Figure 2 displays the mean gaze durations and reading latencies for the house numbers (upper panel) and the clock times (lower panel).

Errors

Participants made an equal amount of errors in both modes of response [$F_1(1, 19) = 2.52$, $p < .5$; $F_2(1, 84) = 6.25$, $p < .05$].

Reading Latencies

Reading latencies were on average 21 milliseconds shorter in the clock time mode than in the house number mode [$F_1(1, 19) = 2.62$, $p < .5$; $F_2(1, 84) = 67.77$, $p < .001$]. Moreover, reading latencies depended on type [$F_1(11, 209) = 2.82$, $p < .05$;

$F_2(11, 84) = 1.75$, $p < .08$]. Furthermore, the effect of type depended on the mode [$F_1(11, 209) = 2.18$, $p < .05$; $F_2(11, 84) = 2.07$, $p < .05$].

Table 2. *Mean Latencies for the Vocal Responses (M, in Milliseconds) and their Standard Deviations (SD), Gaze Shifts (M, in Milliseconds) and their Standard Deviations (SD), and Error Percentages (E%) per Mode and Type for Experiment 2.*

	Mode									
Type	House number					Clock time				
	Vocal		Gaze			Vocal		Gaze		
	M	SD	M	SD	E%	M	SD	M	SD	E%
00	531	150	609	208	4.8	491	127	519	153	4.2
05	543	152	886	282	4.9	505	151	843	250	6.5
10	539	159	897	340	7.3	516	139	797	220	3.8
15	522	156	956	270	5.4	515	144	788	201	4.6
20	541	159	953	294	4.9	529	149	989	255	5.0
25	535	163	1253	335	7.0	530	157	1008	254	6.9
30	536	156	939	282	6.1	495	131	555	184	4.4
35	540	160	1221	304	6.0	515	153	1069	289	4.8
40	533	152	1009	329	7.1	525	161	1019	250	2.9
45	538	161	1266	315	6.3	513	143	778	208	5.8
50	529	153	974	332	6.0	517	149	768	224	4.6
55	534	158	1303	337	8.5	520	140	780	200	7.1
Total	535	157	1022	361	6.2	514	146	826	281	5.0

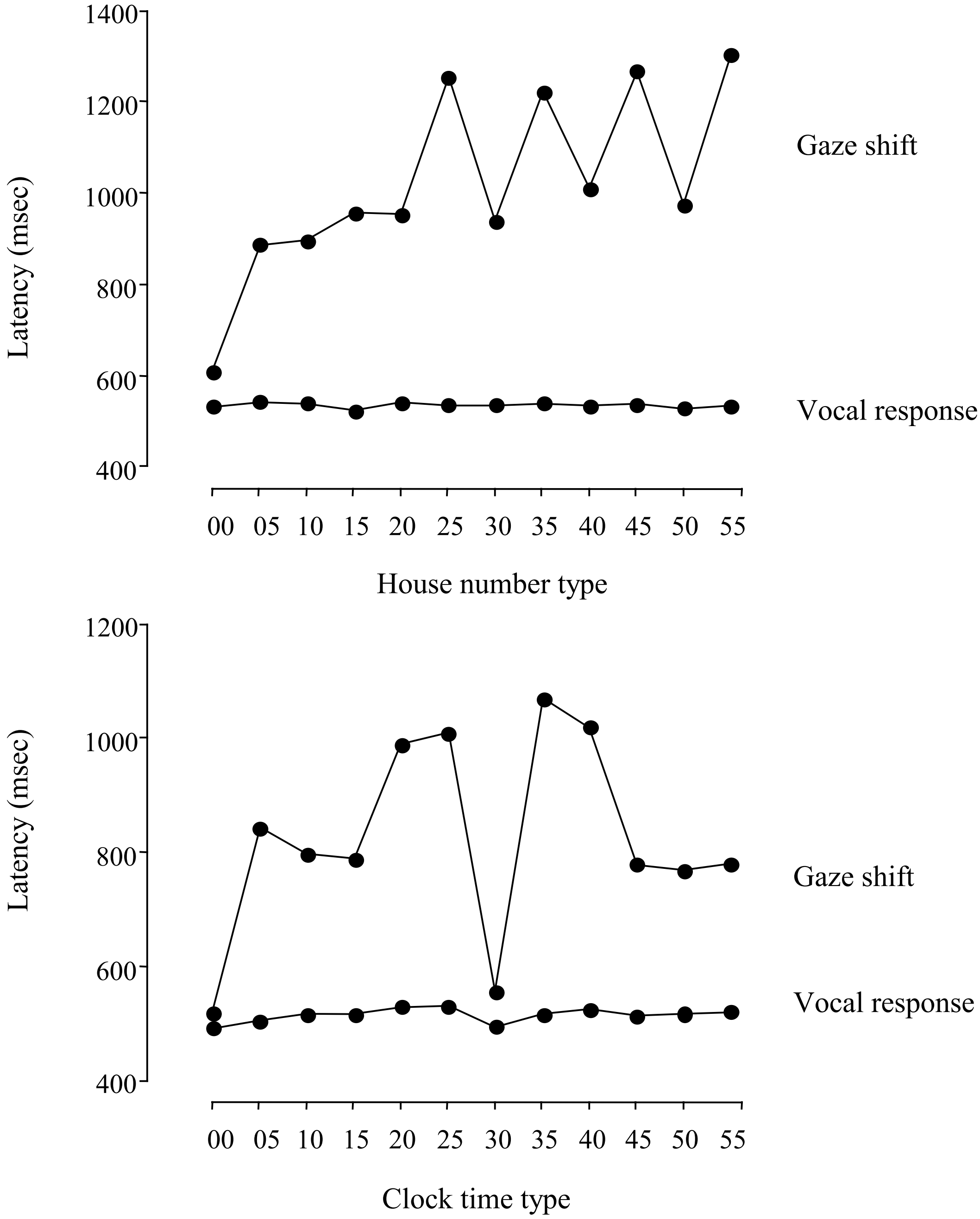

Figure 2. *Mean latencies of the vocal response and the shift of gaze in reading house numbers and clock times in Experiment 2.*

To gain further insight in the factors underlying the interaction between type and mode, we ran multiple regression analyses over the total data set. The same predictor variables as in Experiment 1 were entered into the analyses. We fitted a multi-level multiple regression model to the data with the logarithm of reading latencies as dependent variable and participant as error stratum. We inspected the distribution of the reading latencies. Even after a logarithmic transformation to remove the skewing usually observed for reaction time distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest and longest reading latencies. Removal of individual data points with an RT lower than 350 ms or greater than 1200 ms for both response modes led to a distribution that was approximately (log) normal.

As in Experiment 1, none of the factors made a significant contribution to the reading latencies of the house numbers in the regression analysis. As shown by the upper panel of Figure 2, the reading latencies did not differ much among the twelve number types, despite there being considerable differences in numeral length among types.

The same predictor variables as in Experiment 1, including those coding the utterance referent and the distance from the referent in minutes, were entered into the analysis of the reading latencies of the clock times. The best-fitting regression model for the clock time mode included one factor, namely the logarithm of morpheme frequency. We observed significant effects for the predictor variable. A greater log morpheme frequency led to longer reading latencies [$t(4891) = 7.09$, $p < .0001$].

Furthermore, the model included two random effects: participant (estimated standard deviation = 0.1730) and an interaction of participant and trial number (estimated standard deviation = 0.0003, log-likelihood ratio = 87.42, $p < .0001$). In addition, the random effects (participant and trial) were pairwise correlated (-0.53; i.e., slower participants gained more speed during the experiment than did fast participants). The standard deviation of the residual error in the model was 0.171. The correlation between the observed and predicted reading latencies was 0.63, indicating a multiple R^2 of 40%. Adding an additional group of factors did not significantly increase the amount of variance accounted for (e.g., utterance referent [$F(1, 5168) = 0.46$, $p = 0.50$], distance from referent [$F(1, 5168) = 0.14$, $p = 0.71$]). These multiple regression results suggest that morphophonological planning factors, but not conceptual factors, determine reading latencies for clock times, replicating Meeuwissen at al. (2003).

Gaze Durations

Gaze durations were on average 196 milliseconds shorter for the clock times than for the house numbers [$F_1(1, 19) = 57.80$, $p < .001$; $F_2(1, 11) = 959.91$, $p < .001$], as indicated by Table 2. Moreover, gaze durations depended on type [$F_1(11, 209) = 288.28$, $p < .001$; $F_2(11, 84) = 217.73$, $p < .001$]. Furthermore, the effect of type varied with response mode [F_1 $(11, 209) = 128.38$, $p < .001$; F_2 $(11, 84) = 70.65$, $p < .001$].

To gain further insight in the factors underlying the interaction between type and mode, we ran multiple regression analyses over the total data set. The predictor variables used for the analysis of the reading latencies were also entered in the analysis of the gaze durations. We inspected the distribution of the gaze durations. Even after a logarithmic transformation to remove the skewing usually observed for gaze duration distributions, a significant departe of normality remained visible in quantile-quantile plots. This non-normality turned out to be due to the shortest and longest gaze durations. Removal of individual data points with a GD lower than 400 ms or greater than 2000 ms for both response modes led to a distribution that was approximately (log) normal.

The best-fitting regression model for the house numbers included three predictor variables, namely the logarithm of the whole-form frequency, the logarithm of the morpheme frequency, and numeral length (i.e. the number of morphemes, phonemes and syllables). We observed significant effects for all three predictors in the model. A greater log whole-form frequency led to shorter gaze durations [$t(5550) = -15.99$, $p < .0001$]. Likewise, a greater morpheme frequency led to shorter gaze durations [$t(5550) = -2.54$, $p < .05$]. Longer numerals elicited longer gaze durations for the number of morphemes [$t(5550) = 7.20$, $p < .0001$], for the number of phonemes [$t(5550) = 4.43$, $p < .0001$], and for the number of syllables [$t(5550) = 7.79$, $p < .0001$]. As shown by the upper panel of Figure 2, utterances mentioning an additional morpheme (e.g., house numbers ending on a 5, like 235 requiring the response "tweehonderd*vijfen*dertig") were looked at much longer than shorter utterances (e.g., house numbers ending on a 0, like 230 requiring the response "tweehonderddertig"). All effects remained significant in sequential analyses of variance, that is, after partialing out the variance contributed by the other two variables ($p < .0001$ for all analyses).

Furthermore, we observed two random effects: participant (estimated standard deviation = 0.2144), and an interaction of participant and trial number, indicating that gaze durations became shorter over trials (estimated standard deviation = 0.0005, log-likelihood ratio = 151.11, $p < .0001$). In addition, the random effects (participant and trial) were pairwise correlated (-0.68; i.e., decrease in gaze durations during the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.178. The correlation between the observed and predicted gaze durations was 0.79, indicating a multiple R^2 of 63%. Adding an additional group of factors did not significantly increase the amount of variance accounted for.

To summarize, the multiple regression results show that in the oral reading of pairs of house numbers, the gaze durations for the first house number of a pair are determined by morphophonological factors such as the logarithm of whole-form frequency, the logarithm of morpheme frequency, and numeral length (i.e., the number of phonemes, morphemes, and syllables). However, conceptual level factors, such as absolute magnitude and its logarithm, did not play a role. This replicates earlier findings on the latencies of reading single house numbers (Meeuwissen et al., 2003).

The best-fitting regression model for the clock times included three predictor variables, namely the logarithm of the whole-form frequency, the logarithm of the morpheme frequency, and numeral length (i.e., the number of phonemes). We observed significant effects of all three predictor variables. A greater log morpheme frequency led to longer gaze durations [$t(5539) = 5.34$, $p < .0001$]. In contrast, a greater log whole-form frequency elicited shorter gaze durations [$t(5539) = -10.37$, $p < .0001$]. Furthermore, longer clock times (i.e., in terms of the number of phonemes) elicited longer gaze durations [$t(5539) = 43.70$, $p < .0001$].

All effects remained significant after partialing out the variance contributed by the other two variables ($p < .0001$ for all analyses). Furthermore, the best-fitting model included two random effects: participant (estimated standard deviation = 0.1928), and an interaction of participant and trial number (estimated standard deviation = 0.0003, log-likelihood ratio = 64.30, $p < .0001$), indicating that gaze durations became shorter during the experiment. In addition, the random effects (participant and trial number) were pairwise correlated (-0.66; i.e., decrease in gaze durations in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.186. The correlation between the observed and predicted gaze durations was 0.75, indicating a multiple R^2 of 56%. Adding an additional group of factors did not significantly increase the amount of variance accounted for. To summarize, the multiple regression results show that when conceptual preparation is made unnecessary by presenting clock times in alphabetic format, gaze durations are determined by morphophonological factors only. Conceptual variables (utterance referent and distance in minutes) did not determine gaze durations for clock time reading. This replicates earlier findings for reading latencies (Meeuwissen et al., 2003).

DISCUSSION

As in Experiment 1, we observed that the gaze durations for the house numbers were determined by morphophonological factors. Again, we observed a dissociation between response latencies and gaze durations. Moreover, whereas the gaze durations for the clock times in Experiment 1 reflected both morphophonological and conceptual factors, the gaze durations in Experiment 2 only reflected morphophonological factors. This suggests that when clock times have to be read aloud, conceptual preparation is no longer required, which corroborates previous findings (Meeuwissen et al., 2003).

The absence of a conceptual involvement (i.e., utterance referent and distance in minutes) in the reading of clock times can be illustrated by comparing the gaze durations for the full hour and the half hour between naming (Figure 1) and reading (Figure 2). As shown by the lower panel of Figure 1, the gaze durations were much shorter for the full hour than for the half hour (i.e., 633 ms versus 920 ms, respectively). This supports the theoretical claim that conceptual transformations are carried out on the minute information (e.g., the 30 in 2:30 has to be transformed into “half past”) and the hour information (e.g., the 2 in 2:30 has to be tranformed into “three”) for the half hour but not for the full hour (e.g., the 2 in 2:00 remains “two”). In contrast, no conceptual transformations are required in reading clock times (e.g., “half drie” has to be produced in response to HALF DRIE). Consequently, the gaze durations should only be determined by morphophonological factors, such as the number of morphemes to be planned for production. Since the full hours (e.g., DRIE UUR) and the half hours (e.g., HALF DRIE) are comparable in numeral length (e.g., they have the same number of morphemes), gaze durations should be comparable as well, which corresponds to what is empirically observed (see Figure 2).

Overall, clock times were looked at much shorter than house numbers. This difference might be due to differences in input length (in terms of number of letters), as clock times (on average, 13 letters) were on average shorter in length than house numbers (on average, 19 letters). Furthermore, house numbers are conventionally written out as a connected string of letters, making them harder to discern.

GENERAL DISCUSSION

The present study examined response latencies and gaze durations in planning the production of complex spoken numerals for time and space. Complex numeral pairs had to be named (Experiment 1) or read aloud (Experiment 2) as house numbers or as clock times. Conceptual planning factors, such as magnitude and its logarithm, did not determine gaze durations for naming and reading aloud house numbers. However, gaze durations for the first house number in a pair reflected the time to plan the corresponding word forms in both naming and reading aloud. The gaze durations for naming are in line with the evidence obtained by Pynte (1974) and Gielen et al. (1991) for silent naming. Gaze durations for the first clock time in a pair reflected, in addition, conceptual factors (i.e., utterance referent and distance in minutes) in naming but not in reading. These findings on the gaze durations for the first numeral in a pair replicate earlier findings obtained for the naming and reading latencies of single clock times (Meeuwissen et al., 2003, in press). However, we observed dissociations between response latencies and gaze durations. For the naming and reading of house numbers, response latencies did not reflect morphophonological factors, whereas gaze durations did. Moreover, numeral length determined the gaze durations but not the response latencies for both house numbers and clock times. Table 3 lists the factors that made a significant contribution to the multiple regression models for each task (naming, reading) and mode (house number, clock time).

The dissociations between gaze durations and response latencies suggest that speakers set different criteria for the onset of articulation and shift of gaze. The dissociation was greater for the house numbers than for the clock times. For the house numbers, none of the factors that influenced the gaze durations were reflected in the response latencies, whereas for the clock times, the dissociation concerned numeral length and log whole-form frequency. Numeral length influenced the gaze durations but not the response latencies for both naming and reading clock times. In addition, the logarithm of the whole-form frequency determined gaze durations but not response latencies in clock time reading.

Table 3. *Summary of the Multiple Regression Analyses. For each Task (Naming, Reading) and Mode (House Number, Clock Time), the Factors are Listed That Made a Significant Contribution to the Regression Model.*

Task	Mode	Response latencies	Gaze durations
naming	house number	none	log whole-form frequency
			log morpheme frequency
			numeral length
	clock time	utterance referent	utterance referent
		distance in minutes	distance in minutes
		log morpheme frequency	log morpheme frequency
			numeral length
reading	house number	none	log whole-form frequency
			log morpheme frequency
			numeral length
	clock time	log morpheme frequency	log morpheme frequency
			log whole-form frequency
			numeral length

The reason why the dissociation was greater for the house numbers than for the clock times may be that the structure of the house number utterances was more predictable than the structure of the clock time utterances. The structure of the house numbers was always x *honderd* z, whereas the structure of the clock times was x *uur*, y *over* x, y *voor* x, y *over half* x, y *voor half* x, *kwart over* x, and *kwart voor* x. The predictable structure of the house numbers allows for minimal planning before the onset of articulation, as the second term in the utterance ("honderd") is predetermined.

When a speaker starts articulation after the number preceding the term "honderd" has been planned, there may be enough time to plan the rest of the house number during the articulation of the first number and the term "honderd". One would expect to obtain a fairly constant response latency pattern, since the particular numerals involved (i.e., "twee" to "negen") are comparable in length (e.g., in terms of number of morphemes and phonemes), as empirically observed. Independent evidence for minimal planning before the onset of articulation was obtained by Schriefers and Teruel (1999), who observed that when speakers produce adjective-noun phrases in response to pictured objects, they often only plan the first syllable of the adjective before speech onset. Schriefers and Teruel argued that speakers are more likely to use small advance planning units when long, complex utterances have to be generated compared to shorter utterances.

This provides an explanation for the discrepancy between the current findings and the results of previous studies (Meeuwissen et al., 2003, in press). Meeuwissen et al. (2003) obtained evidence in response latencies for conceptual and morphophonological planning in naming and reading of single numerals. However, in the present study, the naming and reading of numeral *pairs* was investigated, yielding dissociations between response latencies and gaze durations. Whereas gaze durations reflected the effects of conceptual and morphophonological speech planning variables as found earlier, response latencies did not. Apparently, the criteria for articulation onset differ for the production of short (single numeral) versus long (multiple numerals) utterances.

To conclude, two experiments were reported that examined gaze durations in planning the production of pairs of house numbers and clock times. Gaze durations for naming and reading house numbers were determined by morphophonological variables. Moreover, gaze durations and response latencies for naming but not for reading clock times reflected additional conceptual variables. However, none of the variables determined the naming and reading latencies for house numbers, indicating a dissociation between response latencies and gaze durations. Moreover, numeral length determined the gaze durations but not the response latencies for house numbers and clock times. These results suggest that speakers adopt different criteria for articulation onset and shift of gaze for long utterances, both in naming and oral reading.

NAMING ANALOG CLOCKS CONCEPTUALLY FACILITATES NAMING DIGITAL CLOCKS

CHAPTER 4

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ABSTRACT

This study investigates how speakers of Dutch compute and produce relative time expressions. Naming digital clocks (e.g., 2:45, say "quarter to three") requires conceptual operations on the minute and hour information for the correct relative time expression. The interplay of these conceptual operations was investigated using a repetition-priming paradigm. Participants named analog clocks (the primes) directly before naming digital clocks (the targets). The targets referred to the full hour (e.g., 2:00), the half hour (e.g., 2:30), or the coming hour (e.g., 2:45). The primes differed from the target in one or two hours and in five or ten minutes. Digital clock naming latencies were shorter with a five- than with a ten-minute difference between prime and target, but the difference in hour had no effect. Moreover, the distance in minutes had only an effect for the half hour and the coming hour, but not for the full hour. These findings suggest that conceptual facilitation occurs when conceptual transformations are shared between prime and target in telling time.

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INTRODUCTION

Over the past few decades, there has been an increased interest in numerical cognition and its relation to natural language. Whereas number comprehension and arithmetic processes have been intensively investigated in chronometrical, developmental, neuroimaging, and neuropsychological studies (for reviews, Butterworth, 1999; Dehaene, 1997), the production of spoken numerals has not received much attention. Moreover, of the few studies that have been conducted, most have concentrated on the production of relatively simple numerals like those represented by one- and two-digit Arabic numerals (e.g., saying "twenty" in response to 20; cf. Brysbaert, 1995; Fias, Reynvoet, & Brysbaert, 2001). The production of complex numerical expressions like those involved in time telling (e.g., saying "quarter to three" in response to 2:45) has been almost completely ignored. Yet, being able to produce complex numerical expressions is an essential numerical skill of adult speakers. Moreover, speakers regularly produce these complex numerical expressions. Thus, no theory of numerical cognition or speech production is complete without an account of the production of complex numerical expressions. The research reported in the present paper might gain insight into certain aspects of the planning processes that underlie the production of complex numerical expressions. In particular, we report an experimental study that examined aspects of time telling by native speakers of Dutch.

In one of the first comprehensive experimental studies (to our knowledge *the* first study) of clock time naming, Bock, Irwin, Davidson, and Levelt (2003) compared time telling by English and Dutch speakers. Dutch and English are closely related languages, yet they differ in their basic expressions for telling time. Whereas English time expressions only make reference to the hour (e.g., the past hour in "ten past *two*" [2:10] and "twenty past *two*" [2:20] and the coming hour in "quarter to *three*" [2:45]), Dutch time expressions also make reference to the half hour (the same holds for other Germanic languages like German). This secondary reference point in Dutch operates between the ten minutes before and the ten minutes after the half hour, yielding (in literal translations) "ten after *two*" for 2:10, "ten before *half three*" for 2:20, and "quarter to *three*" for 2:45. Time expressions in Dutch and English can be relative or absolute. In relative expressions, the relation between the (half) hourly reference point and the minute is explicitly mentioned (e.g., by *past* in "ten past two" in English), whereas in absolute expressions it is not (e.g., “two-ten” in English). Furthermore, in relative expressions the reference point changes between the past hour and the coming hour (compare “ten past *two*” for 2:10 with “quarter to *three*” for 2:45), whereas in absolute expressions it remains the same (e.g., “*two* forty-five” for 2:45). Bock et al. (2003) found that American English speakers strongly favor absolute over relative expressions, whereas Dutch speakers strongly prefer relative to absolute expressions. The preferences did not differ between analog and digital clocks. Moreover, Bock et al. had English and Dutch speakers tell the time from analog and digital clocks while recording the speakers' eye movements and naming latencies. The data revealed a tight link between the way clock displays are visually inspected by a speaker and the subsequent production of the time expressions. It seems that within 300 ms after the presentation onset of a clock, a speaker constructs a conceptual representation of the time information to be expressed, which is used to incrementally generate the corresponding spoken utterance.

Recently, we (Meeuwissen, Roelofs, & Levelt, 2003) developed a working model (Figure 1) for the conceptual operations involved in relative time telling in Dutch within the framework of the theory of lexical access in speech production advanced by Levelt, Roelofs, and Meyer (1999; Roelofs, 1992, 1997, 2003). This theory holds that the conceptually driven planning of spoken utterances is a staged process, traversing from conceptual preparation to the initiation of articulation. Three planning levels are distinguished: conceptual preparation, lemma retrieval, and form encoding. Conceptual preparation involves the construction of a conceptual representation (in terms of lexical concepts and their relationships) for the information to be verbally expressed. Lemma retrieval involves the retrieval of memory representations of the syntactic properties of the lexical items expressing the conceptual information. After having selected lemmas, the form of the utterance is encoded, which includes access to the required morphological, phonological, and phonetic information. Telling the time from an analog clock in Dutch (e.g., “kwart voor drie”, English “quarter to three”) involves determining the hours and minutes from the hands of the clock and conceptually determining the reference point (full hour, half hour, or coming hour) and the distance from the reference point in minutes. Next, the corresponding lemmas need to be retrieved (e.g., *kwart*, English *quarter*; *voor*, English *to*; and *drie*, English *three*) and syntactically ordered. Finally, the corresponding morphemes (e.g., <kwart>) and phonemes (/k/, /w/, etc.) need to be retrieved, the phonemes should be syllabified, and the corresponding motor programs need to be recovered. Naming digital clock times (e.g., 2:45) minimally involves determining the hours and minutes from the digits in the input, conceptually determining the reference point (for 2:45 this is the coming hour, i.e., three) and the distance from the reference point in minutes (i.e., 15), retrieving the corresponding lemmas (the lemma *kwart* for 15 and the lemmas of *voor* and *drie*) and syntactically ordering them, retrieving the corresponding morphemes and phonemes, syllabifying the phonemes, and recovering the corresponding motor programs.

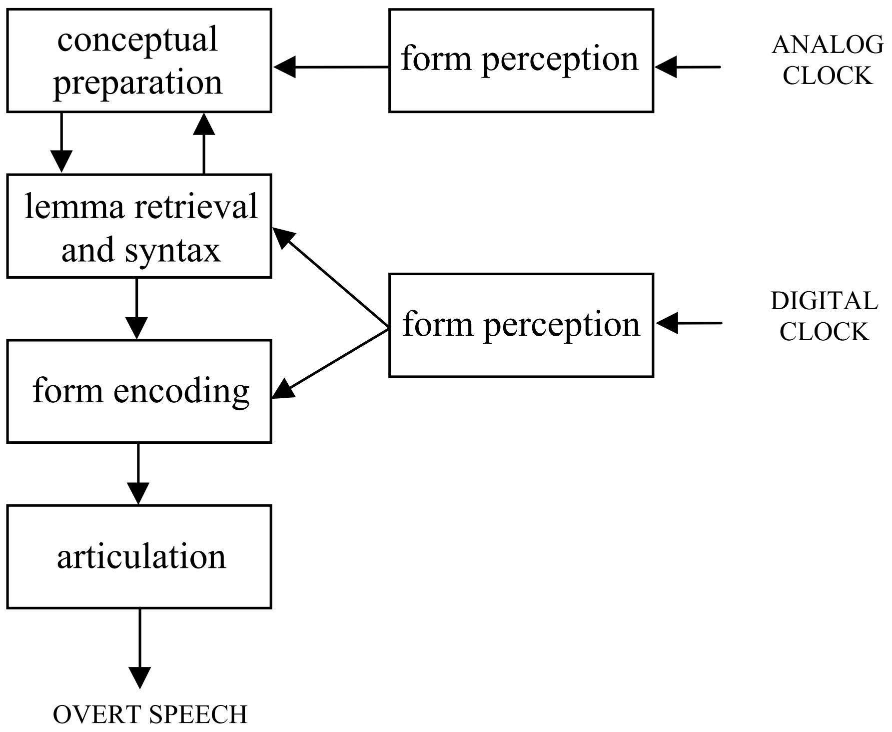

Figure 1. *Planning levels in digital and analog clock time naming.*

We reported evidence for the engagement of these planning levels in the production of clock times (Meeuwissen et al., 2003). In two experiments conducted in Dutch, we compared the production of clock times and house numbers in response to three-digit Arabic numerals as stimuli, which ranged from 200 to 955 in steps of 5. For example, the participants said "op driehonderdvijfenveertig" ("at three-hundred forty-five") to 345 and "om kwart voor vier" ("at quarter to four") to 3:45. Multiple regression analyses showed that the naming latencies for the house numbers were mostly determined by morphophonological factors such as the number of phonemes and morphemes and by morpheme frequency. In contrast, the latencies of the clock time naming revealed a strong additional conceptual involvement. The latency patterns here were best explained by assuming a number of conceptual operations applied to the input (e.g., 3:45 should be conceptually transformed into quarter to four). A second study showed that when these conceptual operations were made unnecessary by presenting alphabetically written numerals as stimuli (e.g., DRIEHONDERDVIJFENVEERTIG, English "three hundred forty-five"; KWART VOOR VIER, English "quarter to four"), only morphophonological factors determined the production latencies in both response modes. These results indicate that different planning levels are engaged in spoken numeral production depending on the response mode and perceptual input format.

As concerns the conceptual preparation required for digital clock time naming, the differences in reference point (full hour, half hour, coming hour) were reflected in the naming latencies. Utterances referring to the full hour were produced faster than utterances referring to the half hour and the coming hour. Furthermore, the differences in minutes were also reflected in the naming latencies. Utterances mentioning a ten minute distance from a reference point were produced slower than utterances mentioning a five minute distance, and these were produced slower than utterances that expressed a zero distance.

We explained these findings on the conceptual preparation of clock time expressions in terms of a procedural semantics for clock time naming. In constructing a conceptual representation for a clock time on the basis of digital input, a speaker of Dutch has to determine the reference point and the distance in minutes. For a given three-digit input X:YZ, a procedure is assumed that, as a first step, determines the reference point. If YZ is smaller than 20, the reference point is x, if it falls between 20 and 40, the reference point is half (x + 1), and if it is larger than 40, the reference point is (x + 1). If adding an hour takes time, utterances referring to the full hour ("x") should be produced faster than those referring to the coming hour ("x + 1") and the half hour ("half (x + 1)"), as we empirically observed. Our data suggested that, overall, specifying a five minute distance takes less time than specifying a ten minute distance. However, the effect of the minutes (five versus ten) depended on the reference point (full hour, half hour, coming hour). The difference between specifying five and ten minutes was around 25 ms for the half hour and the coming hour, but it was only 5 ms for the full hour. This was explained by referring to the fact that specifying the minutes relative to the half hour and coming hour requires a numerical transformation of the input (e.g., the 20 in 2:20 has to be transformed into ten minutes for "tien voor half drie", in English literally "ten before half three" and the 25 in 2:25 into five minutes for "vijf voor half drie", in English literally "five before half three"), whereas such transformations are not required for the full hour (e.g., the 05 in 2:05 remains five minutes for "vijf over twee", in English "five past two", and the 10 in 2:10 remains ten minutes for "tien over twee", in English "ten past two"). In summary, the findings for the clock times were taken to support a procedural semantics in which reference point and distance in minutes information from the digital input had to be conceptually transformed in order to produce the correct relative time expression.

PRESENT STUDY

This current study investigated the interplay of these conceptual operations using a repetition priming paradigm (cf. Bock, 1986; Bock & Griffin, 2000; Bock & Loebell, 1990; Wheeldon & Monsell, 1994). We investigated whether naming an analog clock (the prime) before naming a digital clock (the target) has an effect on target production latencies. Participants told the time from an analog clock directly before telling the time from a digital clock. The digital target clock times referred to the full hour (e.g., 2:00), the half hour (e.g., 2:30), or the coming hour (e.g., 2:45). The analog clock primes differed from the targets in one or two hours and in five or ten minutes. As a control priming condition, we considered to include an analog clock without any time information or an analog clock that displays the same time as the target. However, there are several problems with these candidate control conditions. When the prime contains no time information, the task for prime and target is different (i.e., all primes would require an oral response except for the control condition). And there would be full conceptual and form overlap when prime and target would display the same time. Since we were not interested in determining whether priming produces "absolute" facilitation or interference but only in assessing whether conceptual priming of minute and hour information occurs, we decided to include no "neutral" control condition.

In our experiment, participants named an analog clock as prime before naming a digital clock. Other prime-target combinations are of course possible, such as an analog clock as prime for an analog clock or a digital clock as prime for a digital clock. However, with such prime-target combinations there would be visual overlap between prime and target, making it difficult to assess the conceptual contribution. So, in order to pick up the "true" conceptual contribution, it is important that primes and targets share no visual overlap. This is the case in our study.

If aspects of conceptual transformations (i.e., procedure applications or memory retrievals) are shared between naming analog and digital clocks, repetition priming effects should be obtained. Whereas determining the reference point from analog clocks is based on the spatial position of the big hand of the clocks, determining the reference point from digital clocks is based on the last two digits specifying the minutes, as explained earlier. If the number of minutes specified by the big hand or the last two digits is smaller than 20, the reference point is x, if it falls between 20 and 40, the reference point is half(x + 1), and if it is larger than 40, the reference point is (x + 1). For analog clocks, the value of x is determined by the spatial position of the small hand and for digital clocks the value is determined by the first, leftmost digit. Given that all these operations differ between display formats (using the spatial position of the hands versus using digital information), one expects that priming the reference points has no effect. In contrast, determining the distance in minutes relative to the reference point seems to have certain aspects in common between naming digital and analog clocks. In particular, if the minute information is encoded into the same conceptual format for digital and analog clocks, determining the minutes relative to the reference point can be performed in the same way for both clock types. Consequently, one expects repetition priming for a difference in minutes between prime and target.

METHOD

Participants

Eighteen speakers participated in the experiment. They were undergraduate students of Nijmegen University, native speakers of Dutch, and they had normal or corrected-to-normal vision. They were paid for their participation.

Materials and Design

Three types of digital clock times were used as targets, henceforth referred to as *type*: the full hour (2:00, 3:00, …, 9:00), the half hour (2:30, 3:30, …, 9:30), and quarter to the coming hour (2:45, 3:45, …, 9:45). Of each target type, there were 8 instances (e.g., for the hour, the instances were 2:00, 3:00, 4:00, 5:00, 6:00, 7:00, 8:00, and 9:00). The primes consisted of analog clocks with big and small hands but not containing any numbers or interval marks. The primes depicted times from the 12-hour period between 12:00 and 11:55 in five-minute intervals. Primes differed in time from the targets both on the *hour* (one versus two hours) and *minute* (five versus ten minutes) dimension. Primes depicted times that were always later than targets. For example, for the target 2:00 (say "twee uur", English "two o'clock"), analog clock primes would elicit utterances like "vijf over drie" (English "five past three"), "tien over drie" (English "ten past three"), "vijf over vier" (English "five past four"), or "tien over vier" (English "ten past four"). A similar approach was taken for the other two target types, with primes either being one hour and five minutes, one hour and ten minutes, two hours and five minutes, or two hours and ten minutes later than the targets.

Table 1 lists example utterances for each of the four prime conditions and each of the three target types. Note that for the target type of quarter to the coming hour (e.g., 2:45), analog clock primes would elicit utterances like "*tien* voor vier" (English "*ten* before four") resulting in a one-hour and five-minute difference between prime and target, and "*vijf* voor vier" (English "*five* to four") resulting in a one-hour and ten-minute distance between prime and target. Whereas the prime utterances express a five or ten minutes distance from the coming hour, the distance from the target reference point (i.e., quarter to the coming hour) is the reverse. For example, the distance between the prime "*vijf* voor vier" (English "*five* to four") and the target "kwart voor vier" ("quarter to four") is ten rather than five minutes. We expected that the distance from the target expression is critical (e.g., ten minutes), not the number of minutes specified in the prime expression (e.g., *five*).

Table 1. *Example utterances for each prime condition and each target type, with literal English translations between parentheses. Primes were 1 hour and 5 minutes, 1 hour and 10 minutes, 2 hours and 5 minutes, and 2 hours and 10 minutes later than the target.*

Prime condition (distance)		Prime utterance (analog display)	Target utterance (digital display)
Hour	Minute		Full hour
1	5	"vijf over vier" (five past four)	"drie uur" (three o'clock)
1	10	"tien over vier" (ten past four)	"drie uur" (three o'clock)
2	5	"vijf over vijf" (five past five)	"drie uur" (three o'clock)
2	10	"tien over vijf" (ten past five)	"drie uur" (three o'clock)
			Half hour
1	5	"vijf over half vier" (five past half four)	"half drie" (half three)
1	10	"tien over half vier" (ten past half four)	"half drie" (half three)
2	5	"vijf over half vijf" (five past half five)	"half drie" (half three)
2	10	"tien over half vijf" (ten past half five)	"half drie" (half three)
			Quarter to the coming hour
1	5	"tien voor vier" (ten before four)	"kwart voor drie" (quarter to three)
1	10	"vijf voor vier" (five before four)	"kwart voor drie" (quarter to three)
2	5	"tien voor vijf" (ten before five)	"kwart voor drie" (quarter to three)
2	10	"vijf voor vijf" (five before five)	"kwart voor drie" (quarter to three)

We decided to restrict the experimental targets to the full hour, the half hour, and quarter to the coming hour to prevent a problem associated with the priming of relative clock times in Dutch. Consider, for example, the analog clock for "tien voor half vier" (English "ten before half four") as a prime for the target 3:15. Although the difference between prime and target is only five minutes, the reference point of the prime is simultanously changed by one hour. To avoid such complications, we used only the full hour, the half hour, and quarter to the coming hour as targets. However, to avoid that participants became aware of the prime-target relations, a great number of filler primes and targets were included in the experiment. Filler trials had as targets the full hour, quarter past the hour, the half hour, and quarter to the coming hour, which were combined with filler primes that varied only on the hour or only on the minute dimension with the targets (but not on both dimensions). This introduced phonological overlap between prime and target (e.g., "drie *uur*", English "three *o'clock*" served as prime for "twee *uur*", English "two *o'clock*", or "*vijf* over drie", English "*five* past three" served as prime for "*vijf* over twee", English "*five* past two"). Furthermore, the distance between filler primes and targets could be more than one or two hours and more than five or ten minutes (e.g., "tien voor half vier", English "ten before half hour" served as prime for "twee uur", English "two o'clock"). We controlled for possible voice key artifacts by instructing participants to start each response with the same word, *om* (English *at*) in both analog and digital clock time naming. In this way, the responses in all conditions started with the same phoneme.

The experimental trials were preceded by a block of practice trials containing all the analog clock faces in a random fashion. After the practice block, the experimental analog primes and digital targets were presented in a random fashion, each target occurring once in each of the four prime conditions (one hour and five minutes; one hour and ten minutes; two hours and five minutes; two hours and ten minutes), yielding 96 trials in total (3 target types x 8 instances x 4 prime conditions). In addition, there were 342 filler trials.

Procedure

The clock faces were displayed on a ViewSonic 17PS screen. The experiment was run under the Nijmegen Experiment Setup (NESU). Participants' utterances were recorded over a Sennheiser ME400 microphone to a Sony DTC55 digital audio tape recorder for later transcription. An electronic voice key measured the naming latencies. Participants were tested individually. They were seated in a dimly lit, soundproof cabin in front of the computer monitor. The distance between participant and screen was approximately 50 cm. Preceding the experiment, participants were provided with a written instruction stating that the clocks (both analog and digital) had to be named in a relative way, with some illustrative examples. Furthermore, they were asked to respond in a fluent manner. The structure of a trial was as follows: First, the participant saw a warning signal (an asterisk) for 500 ms, directly followed by the display of an analog clock (the prime) in the middle of the screen for four seconds. This long presentation time for the analog clocks was chosen based on the study by Bock et al. (2003) and a small pilot study. Bock et al. observed that speakers of Dutch start uttering a relative clock time expression from an analog clock on average 1300 ms after display onset. In our pilot study, we observed that participants were able to complete the naming of analog clocks within four seconds. Thus, by displaying the analog clock for four seconds, the participants should be able to complete the naming of the analog clocks before the digital clocks are presented. After displaying an analog clock (the prime), a digital clock (the target) was displayed in the middle of the analog clock for one second. Before the next trial started, the screen went blank for one second. Stimuli were presented in black on a white background. The total duration of the trial was 6.5 seconds. An experimental session lasted about 50 minutes.

Analyses

A trial was considered invalid when it included a mispronunciation, when a wrong response was produced, or when the voice key was triggered incorrectly. Invalid trials were excluded from the statistical analyses of the latencies. The naming latencies and errors for the digital clocks were submitted to by-participant and by-item analyses of variance (ANOVAs). Minute and hour were tested within participants and within items. Target was tested within participants but between items.

RESULTS

Table 2 gives the mean naming latencies, the standard deviations, and the error percentages for the target by hour by minute cells. Figure 2 shows the mean naming latencies for each prime condition.

Errors

The analysis of the errors yielded a main effect of target [$F_1(2, 34) = 4.33$, $p < .03$; $F_2(2, 21) = 4.25$, $p < .03$]. The number of errors was lowest when the target made reference to the full hour (4.0 %), followed by the half hour (5.2 %), and the quarter to the coming hour (8.2 %). As indicated by Table 2, most errors were made in the slowest conditions, so there is no evidence for a speed-accuracy tradeoff. There were no main effects of hour [$F_1(1, 17) < 1$, $p > .61$; $F_2(1, 21) < 1$,

$p > .80$], and minute [$F_1(1, 17) = 2.63$, $p > .10$; $F_2(1, 21) = 2.07$, $p > .16$]. Moreover, there were no two-way or three-way interactions (most Fs < 1).

Table 2. *Mean production latencies (M, in milliseconds), standard deviations (SD), and error percentages (E%) per target type and prime type.*

		Prime					
		Minute					
		5			10		
Target	Hour						
		M	*SD*	*E%*	*M*	*SD*	*E%*
Full hour							
	1	529	103	3.5	510	87	4.9
	2	521	89	4.2	522	101	3.5
	Total	525	96	3.9	516	94	4.2
Half hour							
	1	606	157	2.8	627	153	4.9
	2	608	142	6.3	641	171	6.9
	Total	607	150	4.6	634	162	5.9
Quarter to coming hour							
	1	617	158	7.6	665	170	9.7
	2	622	147	4.9	643	182	10.4
	Total	620	152	6.3	654	176	10.1

Naming latencies

Naming latencies differed depending on target [$F_1(2, 34) = 37.55$, MSE = 7996, $p < .001$; $F_2(2, 21) = 72.57$, MSE = 1758, $p < .001$]. Participants were fastest in producing full hours (on average 521 ms), followed by the half hours (on average 621 ms) and quarter to the coming hours (on average 636 ms).

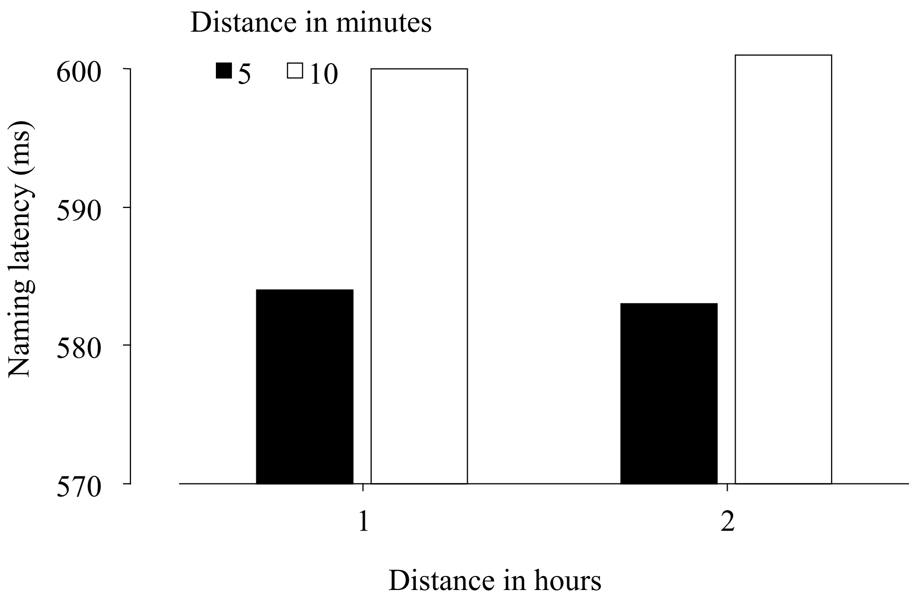

Figure 2. *Target naming latencies in milliseconds collapsed across target type as a function of distance in hours and minutes between prime and target.*

This replicates Meeuwissen et al. (2003), who tested these three target types together with other targets ranging from 2:00 to 9:55 in steps of 5 minutes. Priming the hour had no effect [$F_1(1, 17) < 1$, MSE = 1259, $p > .95$; $F_2(1, 21) < 1$, MSE = 1116, $p > .92$]. However, priming the minutes affected the latencies [$F_1(1, 17) = 6.67$, MSE = 2404, $p < .02$; $F_2(1, 21) = 6.97$, MSE = 1078, $p < .02$] (mean naming latencies were 584 ms for a five-minute distance and 600 ms for a ten-minute distance from the target). There was no interaction between hour and minute [$F_1(1, 17) < 1$, MSE = 2191, $p > .95$; $F_2(1, 21) < 1$, MSE = 1331, $p > .95$]. The effect of the distance in minutes varied with target [$F_1(2,34) = 5.40$, MSE = 1733, $p < .01$; $F_2(2, 21) = 3.98$, MSE = 1078, $p < .04$]. The effect of minute was only obtained for the targets referring to the half hour (27 ms) and quarter to the coming hour (34 ms), whereas the targets referring to the full hour showed no effect (-9 ms). There were no interactions of target and hour [$F_1(2, 34) = 1.68$, MSE = 945, $p > .20$; $F_2(2, 21) < 1$, MSE = 1116, $p > .66$], and of target, hour and minute [$F_1(2, 34) = 2.94$, MSE = 1360, $p > .06$; $F_2(2, 21) < 1$, MSE = 1331, $p > .44$].

DISCUSSION

Earlier research suggested that naming digital clocks involves conceptual operations carried out on the hour and minute information from the digital input (Meeuwissen et al., 2003). The present study investigated the interplay of these conceptual operations using a repetition priming paradigm. Dutch participants told the time from an analog clock (the prime) directly before telling the time from a digital clock (the target). The target clock times referred to the full hour (e.g., 2:00), the half hour (e.g., 2:30), or the coming hour (e.g., 2:45). The prime clocks differed from the target in one or two hours and in five or ten minutes. Digital naming latencies were shorter with a five-minute difference than with a ten-minute difference, whereas the difference in hour had no effect, and there was also no interaction between minute and hour. The distance in minutes had only an effect when the utterance made reference to the half hour or the coming hour, but not when reference was made to the full hour.

The absence of a repetition priming effect for the full hours suggests that determining the reference point [x, half (x + 1), and x + 1] and its value (e.g., x takes the value 3) from the hands of an analog clock does not help to determine the reference point and its value from the digits in a digital clock. This suggests that determining the reference point and its value are different operations for analog and digital clocks. The presence of a repetition priming effect for the minutes suggests that determining the distance from the reference point in minutes for an analog clock helps to determine the distance from the reference point in minutes for a digital clock. This suggests that, once the reference point and the minutes are known, determining the minutes relative to the reference point is the same operation for analog and digital clocks. Moreover, whereas specifying the minutes relative to the half hour and the coming hour requires numerical transformations of the minute information provided by the digital input (e.g., the 20 in 2:20 has to be transformed into ten minutes, the 25 in 2:25 into five minutes, and the 30 in 2:30 into zero minutes) and the hands of an analog clock face (e.g., the thirty minutes determined for half past two should be transformed into zero minutes relative to the half-past reference point), such transformations are not required for the full hour (e.g., the 00 in 2:00 remains zero minutes, the 05 in 2:05 remains five minutes, and the 10 in 2:10 remains ten minutes). This may explain why an effect of minutes is obtained for the half hour and the coming hour, but not for the full hour. Moreover, it may explain why an effect of minutes is obtained both in specifying the conceptual representation for the utterance (Meeuwissen et al., 2003) and also in priming this specification.

Since speakers responded fastest to the full hours, one may wonder whether the absence of a priming effect for the full hour is a floor effect. This seems unlikely, though, upon inspection of Table 2. It appears that a ten-minute difference between prime and target yielded numerically smaller latencies (516 ms) than a five-minute difference (525 ms). Thus, the direction of the priming effect is different for the full hour than for the half hour and the coming hour, which suggests that the priming effect is differently mediated for the full hour than for the other target types, as we suggested.

We examined time telling by speakers of Dutch. Given that the systems for telling time differ between languages, one may wonder whether the present results are specific for the Dutch language. As we explained, whereas English has only an hourly reference point, Dutch has both hourly and half-hourly reference points. In our study, conceptual priming was obtained for both the hourly reference point (i.e., the coming hour) and the half-hourly reference point. Given that both Dutch and English make reference to the coming hour, we expect that the conceptual priming we obtained will also be obtained for English. This may be tested in future research.

To conclude, naming analog clocks conceptually facilitates naming digital clocks. The facilitation is observed for the minutes but not for the hours. This suggests that determining the reference point is accomplished in a different way, whereas determining the minutes relative to the reference point has certain aspects in common for analog and digital clocks. This account predicts that an effect of distance in hour should be obtained when digital clocks are used as primes for naming digital clocks and analog clocks are used as primes for naming analog clocks. The current study has shown that priming is possible without visual overlap between prime and target, which opens the way for testing these predictions in future research.

Relative and Absolute Naming of Analog and Digital Clocks

CHAPTER 5

Marjolein Meeuwissen, Ardi Roelofs, and Willem J. M. Levelt[1]

ABSTRACT

The aim of the present study was to examine the speech planning processes involved in clock time production by contrasting expression format (abolute vs. relative) with clock display (analog vs. digital). Speakers produced relative time expressions (e.g., "quarter to four") in response to analog and digital clocks. In addition, they produced absolute time expressions (e.g., "three forty-five") in response to digital clocks. Naming latencies showed evidence of a similar conceptual involvement, along with morphophonological planning, when relative time expressions had to be produced from either analog or digital clocks. In contrast, naming latencies were determined by morphophonological planning factors only when absolute time expressions had to be produced from digital clocks. These findings suggest that different levels of speech planning that are involved in clock time production. Furthermore, which particular speech planning levels are engaged is determined by expression format rather than by clock display.

[1] An adapted version of this chapter has been submitted for publication.

INTRODUCTION

Time can be displayed and conveyed in different ways. Analog clocks represent time by means of a circle that marks the hour (one to twelve) and the minutes (one to sixty) combined with small and big hands pointing to the current hour and minutes, respectively. In contrast, digital clocks display time by means of a row of three or four digits (e.g., 3:45). The rightmost digits code the minutes and the leftmost digits code the hour. Time can also be conveyed in different ways, namely in relative and absolute ways (see Bock, Irwin, Davidson, & Levelt, 2003, for extensive discussion). For example, in English, one may say "quarter to four" (relative) or "three forty-five" (absolute) in response to the digital clock time 3:45. Relative expressions mention the relation between the hourly reference point and the minutes (by terms like "to" and "past"), whereas absolute expressions do not. Moreover, the reference point changes between the past hour and the next hour in relative but not in absolute expressions. For example, in English it changes after the half hour (compare "twenty past *three*" and "twenty to *four*" with "*three* twenty" and "*three* forty"). In languages such as Dutch, there is a secondary, half-hourly reference point, which operates between twenty and forty minutes past the hour, yielding expressions like "tien voor half vier" (literally "ten before half four") for 3:20. Finally, relative expressions mention the minute before the hour, whereas absolute expressions mention the hour before the minute.

Recently, we (Meeuwissen, Roelofs, & Levelt, 2003, in press, submitted) developed a working model for the speech planning levels involved in clock time production. This model (Figure 1) holds that producing relative time expressions (e.g., "quarter to four") from an analog clock involves both conceptual and morphophonological speech planning. The conceptual involvement can be characterized by extracting the hour (i.e., 4) and minute (i.e., 45) information from the small and big hands from an analog clock and subsequently conceptualizing the reference point (i.e., coming hour) and distance in minutes from that reference point (i.e., fifteen minutes). Next, the corresponding lemmas need to be retrieved (i.e., *quarter*, *to*, and *four*) and syntactically ordered. Finally, the corresponding morphemes (e. g., <quarter>) and phonemes need to be retrieved, syllabified, and articulated. Likewise, producing relative time expressions from digital clocks (e.g., 3:45) involves extracting the hour and minute information from the digits in the input, conceptually determining the reference point (i.e., coming hour) and distance in minutes from that reference point (i.e., fifteen minutes), retrieving the corresponding lemmas (i.e., *quarter*, *to*, and *four*), syntactically ordering them, retrieving the morphemes and phonemes, syllabifying, and articulating them.

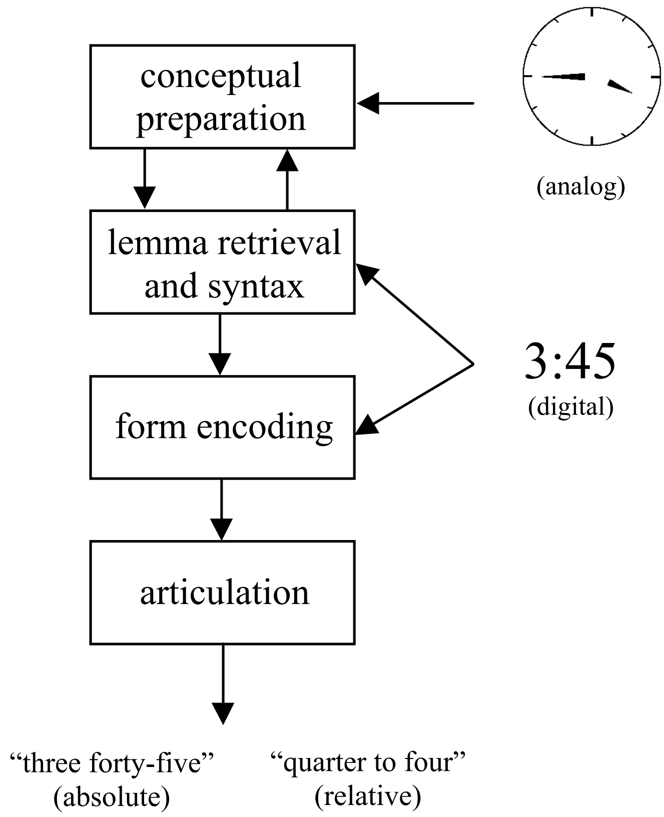

Figure 1. *Planning levels in relative and absolute naming of analog and digital clocks.*

Thus, in our model of clock time production, equivalent speech planning levels are engaged for producing relative time expressions from analog and digital clocks. Empirical evidence for this claim comes from a priming study in Dutch (Meeuwissen et al., in press) in which speakers produced relative time expressions from an analog clock (prime) and directly thereafter from a digital clock (target). Primes differed from targets on both the hour and the minute dimension (i.e., by 1 or 2 hours and 5 or 10 minutes), such that there was no speech overlap between prime and target. For example, the prime would elicit an utterance like “five before five”, whereas the target would elicit the utterance “quarter to four”. We observed significant priming on target latencies for the minute dimension (i.e., shorter latencies with primes differing from the target in 5 compared to 10 minutes), but not for the hour dimension. This agrees with the idea that although analog and digital clocks differ with respect to the initial uptake of minute and hour information from the input (e.g., determining the positions of the big and small hands on an analog clock versus reading the digits in the right and left numerical fields on a digital clock), the subsequent transformation of that information, which is needed to determine the distance in minutes relative to a particular referent, may be carried out in an equivalent manner. Furthermore, Meeuwissen et al. (in press) showed that when such conceptual transformations on the extracted minute information are not necessary, as is the case for full hour utterances (e.g., 2:00) compared to half hour (e.g., 2:30) and coming hour (e.g., 2:45) utterances, no conceptual priming between prime and target was obtained. Together, these findings lend support to the idea that conceptual level speech planning (i.e., transformations of the minute and hour information extracted from a particular clock display) is to some extent shared for telling time from analog and digital clocks.

In contrast, when time is told by producing absolute time expressions, the model holds that a different route through the speech production system is adopted. For producing absolute time expressions (i.e., "three forty-five") from a digital clock (i.e., 3:45) it suffices to read the digits from the input, and subsequently retrieving the corresponding lemmas (i.e., *three*, *forty-five*), recovering the morphemes (i.e., <three>, <forty>, and <five>), retrieving the phonemes, syllabifying them, and articulating them. Hence, according to our model, no conceptual level speech planning is needed for producing absolute time expressions.

PRESENT STUDY

The aim of the present study was to test the specific predictions by our model on Dutch clock time production (Meeuwissen et al., 2003, in press, submitted) by contrasting expression format (absolute vs. relative) and clock display (analog vs. digital clocks). Speakers produced relative time expressions (e.g., "quarter to four") in response to analog and digital clocks. In addition, they produced absolute time expressions (e.g., "three forty-five") in response to digital clocks (we did not test for absolute expressions to analog clocks, because these responses are very odd for Dutch speakers).

First of all, we expected to replicate the naming latency patterns as previously obtained for the production of relative time expressions from digital clocks (cf. Meeuwissen et al., 2003). There, it was shown that response latencies for relative naming of digital clocks varied with utterance referent (i.e., full hours, like 3:00, being produced the fastest, followed by the coming hours, like 3:45, and half hours, like 3:30). Furthermore, naming latencies increased with a greater distance in minutes from a referent (e.g., clock times with a 10 minute distance, like 3:20, were produced much slower than clock times with a 5 minute distance, like 3:25). Furthermore, in addition to these conceptual level factors, naming latencies were determined by morphophonological speech planning factors such as numeral length and frequency (cf. Meeuwissen et al., 2003).

Moreover, from a previous priming study described above (Meeuwissen et al., in press) it was shown that, despite differences in visual input, conceptual operations are carried out in a similar manner for telling time from analog and digital clock displays. Therefore, we predicted that naming latencies for producing relative time expressions from analog clocks should reflect the conceptual level speech planning found earlier for relative naming of digital clocks.

In contrast, when time is told in an absolute way from digital clocks, and the digits in the input can be read aloud, such conceptual involvement is no longer mandatory for speech planning. Instead, we predicted that only morphophonological variables, such as utterance length, should determine naming latencies for producing absolute expressions from digital clocks.

METHOD

Participants

Eighteen speakers participated in the experiment. They were undergraduate students of Nijmegen University, native speakers of Dutch and had normal or corrected-to-normal vision. They were paid for their participation.

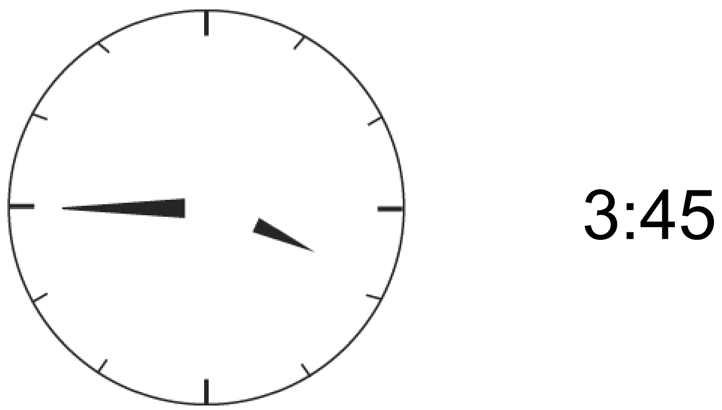

Figure 2. *Examples of analog and digital clock displays.*

Materials

Stimuli consisted of analog and digital clock displays (see Figure 2). Analog clocks were tick-marked, and had parametric hour hands (like regular clocks). Following Meeuwissen et al. (2003, submitted), stimuli ranged from 2:00 to 9:55, ending either on 0 or 5. This yielded 12 different clock types collapsed across the hours: (00) 2:00, 3:00, … (05) 2:05, 3:05, … (10) 2:10, 3:10, … (15) 2:15, 3:15, … (20) 2:20, 3:20, … (25) 2:25, 3:25, … (30) 2:30, 3:30, … (35) 2:35, 3:35, … (40) 2:40, 3:40, … (45) 2:45, 3:45, … (50) 2:50, 3:50, … (55) 2:55, 3:55, … For each *type*, there were 8 instances (e.g., for type (00), the instances were 2:00, 3:00, 4:00, 5:00, 6:00, 7:00, 8:00, 9:00). Furthermore, we controlled for possible voice key artifacts by instructing participants to start each response with the same word *om* (“at”). In this way, responses in all conditions started with the same phoneme.

Design

Each experimental block testing a separate *mode* (i.e., analog relative, digital relative, and digital absolute) randomly presented the 96 stimuli (12 types x 8 instances), which were repeated 3 times, yielding 288 trials per block. A practice block of 6 trials, containing items of each stimulus type, preceded a block of trials. The order in which the experimental blocks were administered was counterbalanced across participants.

Procedure

Participants were tested individually. They were seated in a dimly lit, soundproof cabin, in front of a computer monitor (NEC Multisync) and a Sennheiser microphone. The distance between participant and screen was approximately 50 cm. The experiment was run with the NESU experimental software developed at the Max Planck Institute. Naming latencies were measured using a voice key apparatus. Preceding each experimental block, participants were provided with a written instruction stating how the clocks had to be named (relative or absolute), along with some illustrative examples. Furthermore, they were asked to respond in a fluent manner.

The structure of a trial was as follows. First, the participant saw a fixation cross for 200 msec, directly followed by the display of either an analog clock or a digital clock. Previous research in clock time production has shown that naming latencies differ for analog and digital clocks (cf. Bock et al., 2003), with analog clocks being responded to about 1.5 to 2 times slower than digital clocks. Hence, in the current study, trials for analog clocks lasted 4 seconds, leaving participants enough time to plan and start articulating, and for digital clocks they lasted 2 seconds. Stimuli were presented in white on a black background. Naming latencies were collected for each participant individually, and each trial was recorded using a DAT recorder. An experimental session containing all three blocks lasted about 1 hour.

Analyses

A trial was considered invalid when it included a speech error, a voice key error, a time-out, or when a wrong oral response was given. Invalid trials were excluded from statistical analyses.

The naming latencies and errors were submitted to by-participant (F_1) and by-item (F_2) analyses of variance with the variables mode and type. Interactions of mode and type were further explored through multiple regressions on the total data set.

RESULTS

Table 1 gives the mean naming latencies, the standard deviations, and the error percentages for the three modes. Figure 3 shows the mean naming latencies to the twelve clock time types for producing relative time expressions from analog (upper panel) and digital (middle panel) clock displays, and for producing absolute time expressions from digital clock displays (lowest panel).

Errors

Errors depended on mode [$F_1(2, 34) = 12.65$, $p < .001$; $F_2(2, 168) = 84.28$, $p < .001$]. Participants made more errors while producing relative time expressions from analog clocks (10.4 %) than from digital clocks (6.4 %), and the fewest errors were made while producing absolute time expressions from digital clocks (3.2 %), see Table 1. Furthermore, errors depended on clock time type [$F_1(11, 187) = 4.14$, $p < .001$; $F_2(11, 84) = 4.88$, $p < .001$]. Furthermore, the effect of clock time type varied with mode [$F_1(22, 374) = 3.71$, $p < .001$; $F_2(22, 168) = 3.39$, $p < .001$]. As indicated by Table 1, most errors were made in the slowest conditions, so there is no evidence for a speed-accuracy tradeoff.

Naming latencies

Naming latencies depended on mode [$F_1(2, 34) = 96.17$, $p < .001$; $F_2(2, 168) = 5940.443$, $p < .001$]. As can be seen in Table 1, naming latencies were slower for producing relative time expressions from analog clocks than from digital clocks, and producing absolute expressions from digital clocks was achieved the quickest. Moreover, latencies depended on clock time type [$F_1(11, 187) = 21.14$, $p < .001$; $F_2(11, 84) = 17.09$, $p < .001$]. Furthermore, the effect of clock time type varied with mode [$F_1(22, 374) = 8.79$, $p < .001$; $F_2(22, 168) = 4.84$, $p < .001$].

Table 1. *Mean Naming Latencies (M, in Milliseconds), Standard Deviations (SD), and Error Percentages (E%) per Mode and Type.*

	Mode								
Type	Analog Relative			Digital Relative			Digital Absolute		
	M	*SD*	*E%*	*M*	*SD*	*E%*	*M*	*SD*	*E%*
00	976	279	11.3	576	102	4.6	477	109	1.6
05	988	289	6.0	619	121	3.7	472	105	3.0
10	998	277	9.3	631	127	6.3	481	116	3.0
15	964	285	7.6	625	122	3.0	487	118	2.5
20	1054	277	15.5	748	212	8.6	482	110	2.5
25	1032	295	8.1	692	155	4.6	488	117	2.5
30	1025	249	15.5	670	151	5.3	486	108	2.8
35	1029	272	7.2	675	158	5.6	492	109	7.2
40	1047	287	12.5	759	196	12.7	482	115	3.2
45	1018	300	7.2	679	138	4.6	487	109	3.5
50	1026	291	10.4	706	167	11.1	484	111	3.5
55	1037	277	14.6	673	138	6.3	486	118	3.2
Total	1016	283	10.4	670	159	6.4	484	112	3.2

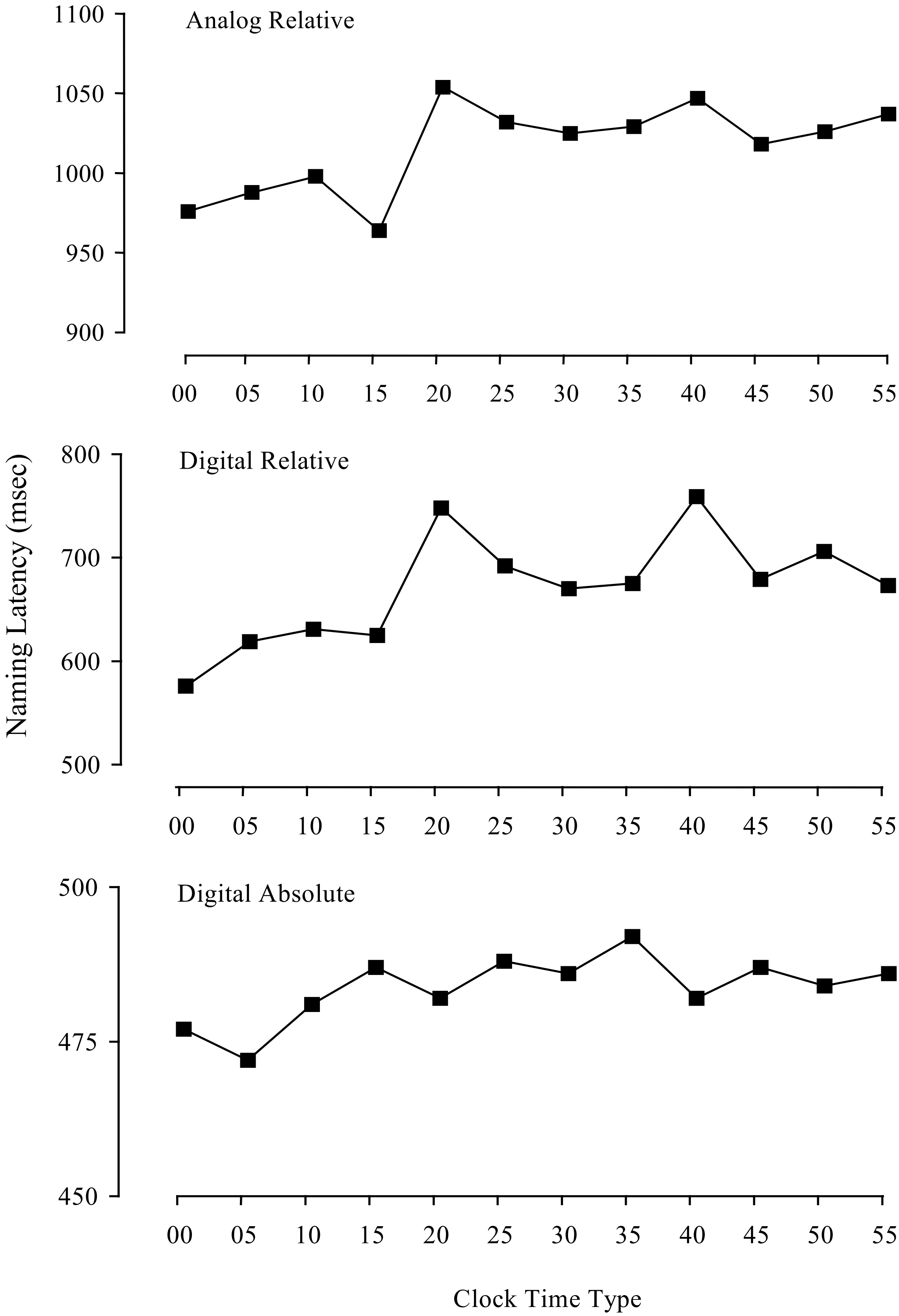

Figure 3. *Mean naming latencies in milliseconds for the production of time expressions.*

To gain further insight in the factors underlying the interaction between mode and clock time type, we ran multiple regression analyses over the total data set. The following three groups of predictor variables were entered into the analyses (identical to Meeuwissen et al., 2003, submitted): (1) *conceptual factors*: utterance referent (i.e., full hour, half hour, or coming hour) and distance from referent (i.e., zero, five, ten, or fifteen minutes); (2) *utterance length*: number of morphemes, number of phonemes, and number of syllables, (3) *frequency*: logarithm of morpheme frequency (CELEX database, Baayen, Piepenbrock, & Gulikers, 1995), and logarithm of whole-form frequency (estimated from a journal-based lexical database, TROUW Corpus). We fitted a multi-level multiple regression model (Pinheiro & Bates, 2000; see also Lorch & Myers, 1990) to the data with the logarithm of the naming latencies as dependent variable and participant as error stratum. In all analyses reported in this paper, we first entered the total set of variables as predictors to assess which made a major contribution. From there, we constructed the best-fitting model. In regression analysis, it is important to check whether the dependent variable is roughly normally distributed (Chatterjee, Hadi, & Price, 2000), as with non-normality, the standard tests of significance may be invalidated. We inspected the distribution of the naming latencies for the analog relative condition. Removal of individual data points with an RT lower than 550 ms led to a distribution that was approximately (log)normal.

The best-fitting regression model for producing relative time expressions from analog clocks included a conceptual factor (i.e., the utterance referent) and frequency (i.e., log morpheme frequency) as predictor variables. We observed significant effects for all two predictor variables. Naming latencies differed for each utterance referent [$t(4555) = 8.90$, $p < .0001$]. As can be seen in the upper panel of Figure 3, utterances referring to the full hour (i.e., 00, 05, 10, 15) were produced much faster than utterances referring to the half hour (i.e., 20, 25, 30, 35, 40) and the coming hour (i.e., 45, 50, 55). Furthermore, a greater log morpheme frequency led to longer response latencies [$t(4555) = 2.59$, $p < .01$]. All effects remained significant after partialling out the variance contributed by the other variable, $p < .01$. In addition, the best-fitting model included two random effects: participant (estimated standard deviation = 0.1721) and an interaction of participant and trial number, indicating that during the experiment participants became faster (estimated standard deviation = 0.0004, log-likelihood ratio =

122.71, $p < .0001$). In addition, the random effects were pairwise correlated: participant and trial (0.068, i.e., the increase in naming latency in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.187. The correlation between the observed and predicted naming latencies was 0.68, indicating a multiple R^2 of 47%. Adding an additional group of factors did not significantly increase the amount of variance accounted for. These multiple regression results suggest that conceptual preparation along with morphophonological planning is involved in the production of relative time expressions from analog clocks.

We inspected the distribution of the naming latencies for the relative digital condition. Removal of individual data points with an RT lower than 350 ms and greater than 1400 ms led to a distribution that was approximately (log)normal. The best-fitting regression model for producing relative time expressions from digital clocks included two conceptual factors (i.e., utterance referent and distance in minutes) and frequency (i.e., logarithm of morpheme frequency) as predictor variables. We observed significant effects for all three predictor variables. Naming latencies differed for each utterance referent [$t(4805) = 22.54$, $p < .0001$]. As can be seen in the middle panel of Figure 3, utterances referring to the full hour (i.e., 00, 05, 10, 15) were produced much faster than utterances referring to the half hour (i.e., 20, 25, 30, 35, 40) and the coming hour (i.e., 45, 50, 55). Furthermore, naming latencies varied depending on the distance in minutes from the referent [$t(4805) = 7.44$, $p < .0001$]. From the middle panel of Figure 3, it can be observed that naming latencies increased with a greater distance in minutes from an utterance referent. Furthermore, a greater log morpheme frequency led to longer naming latencies [$t(4805) = 4.47$, $p < .0001$]. All effects remained significant in sequential analyses of variance, that is, after partialling out the variance contributed by the other two variables ($p < .001$ for all analyses). In addition, the best-fitting model included two random effects: participant (estimated standard deviation = 0.1160) and an interaction of participant and trial number, indicating that during the experiment participants became faster (estimated standard deviation = 0.0005, log-likelihood ratio = 210.08, $p < .0001$). In addition, the random effects were pairwise correlated: participant and trial (-0.29; i.e., the decrease in naming latency in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.170. The correlation between the observed and predicted naming latencies was 0.63, indicating a multiple R^2 of 40%. Adding an additional group of factors did not significantly increase the amount of variance accounted for. These multiple regression results suggest that for the production of relative time expressions from digital clocks conceptual preparation (i.e., determining the correct utterance referent and the distance in minutes from that referent) along with morphophonological planning is required which replicates previous findings (Meeuwissen et al., 2003, submitted).

In contrast, the best-fitting model for producing absolute expressions from digital clocks included only one predictor variable, namely utterance length (i.e., the number of morphemes). In order to achieve a normal distribution of the naming latencies, we included all individual data points with an RT between 200 to 1000 ms. We observed significant effects of the predictor variable. Longer time expressions (i.e., number of morphemes) elicited longer naming latencies [$t(4989) = 2.92$, $p < .01$]. As can be seen in the lowest panel of Figure 3, naming latencies varied consistently with utterance length, yielding a zig-zag pattern ("tien" [10] shorter than "vijftien" [15]; "twintig" [20] shorter than "vijfentwintig" [25]; "dertig" [30] shorter than "vijfendertig" [35]; etc.). Longer time expressions (e.g., "twee uur *vijfen*twintig", literally: "two twenty-five") were produced much slower than shorter utterances (e.g., "twee uur twintig", literally: "two twenty"). Furthermore, we observed two random effects: participant (estimated standard deviation = 0.1362), and an interaction of participant and trial number, indicating that naming latencies became shorter over trials (estimated standard deviation = 0.0006, log-likelihood ratio = 378.64, $p < .0001$). In addition, the random effects were pairwise correlated: participant and trial (-0.35; i.e., the decrease in naming latency in the course of the experiment was greater for slow than for fast participants). The standard deviation of the residual error in the model was 0.170. The correlation between the observed and predicted naming latencies was 65 %, indicating a multiple R^2 of 42%. Adding an additional group of factors did not significantly increase the amount of variance accounted for. These multiple regression results suggest that for the production of absolute time expressions from digital clocks no conceptual speech planning (i.e., determining the utterance referent and the distance in minutes from a referent) is involved. Instead, naming latencies only showed evidence of morphophonological planning (i.e., utterance length).

DISCUSSION

The current study examined the speech planning processes that are involved in clock time production. We investigated alternative means for conveying time by comparing absolute and relative time expressions (e.g., “three forty-five” vs. “quarter to four” respectively). Furthermore, we assessed the contribution of clock display on the levels of speech planning involved by comparing analog and digital clocks.

Overall, we observed that producing absolute expressions from digital clocks is achieved the quickest, followed by producing relative time expressions from digital clocks, and finally producing relative time expressions from analog clocks. For producing absolute time expressions from digital clocks it suffices to read aloud the digits in a left-to-right manner, whereas for producing relative time expressions this mapping of minute and hour information in the input onto the utterance is less straightforward (e.g., 20 in the digital input becomes “ten” in the utterance). Consequently, the three modes (i.e., analog relative, digital relative, and digital absolute) varied in the levels of speech planning involved. Naming latencies showed evidence of a conceptual level involvement along with morphophonological planning when relative time expressions had to be produced from either analog or digital clocks. For both clock displays alike, the production of relative time expressions elicited naming latencies that differed for each utterance referent (i.e., full hours were produced the fastest followed by the coming hours and the half hours) and depending on the logarithm of morpheme frequency, replicating previous findings (Meeuwissen et al., 2003, submitted).

However, we did not find evidence for an additional conceptual preparation component, namely distance in minutes, when relative time expressions were produced from analog clocks. The absence of an effect of minutes on naming latencies for analog clock displays was not anticipated. Inspection of the data for analog clocks (upper panel of Figure 3) revealed that naming latencies increased with a greater minute distance from an utterance referent except for the quarter past the hour. Post-hoc breakdown of naming latencies for the quarter past each hour (i.e., “quarter past two”, “quarter past three”, .., “quarter past nine”) yielded an interesting pattern for this particular time point on an analog clock. For instance, responses were extremely fast (on average 886 msec) to quarter past three, when both hands of the analog clock are collapsed on the quarter. Furthermore, naming latencies tended to increase monotonically with a greater visual angle between the big hand (on the quarter) and the small hand (on the hour). Moreover, such an effect of increasing naming latencies with a bigger visual angle between the hands on an analog clock was not observed for an increasing distance in numbers on the digital clock displays. This suggests a scanning mechanism which is restricted to analog clocks and might be used by the speaker to judge the relative distance from the quarter past to the corresponding hour. Due to the unusually fast responses to the quarter past, the best-fitting model for producing relative time expressions from analog clocks did not include the distance in minutes as a conceptual component. Specifically, the fast responses to the quarter past hided a minute effect. Thus, we can say that, for producing relative time expressions from both analog and digital clocks, conceptual preparation is required, both in terms of hours and minutes.

In contrast, when absolute time expressions had to be produced from digital clocks, naming latencies no longer showed evidence of any conceptual level involvement and were only determined by morphophonological planning variables instead. Producing absolute time expressions turned out to be a homologue of house number naming investigated in earlier research (i.e., compare *x hundred y* with *x o’ y*), see Meeuwissen et al. (2003, submitted). Both house number utterances and absolute time expressions have regular morphosyntactic utterance structures with recurring elements. For house number naming it was shown that no conceptual preparation is required in that naming latencies were only determined by morphophonological variables such as utterance length. The pattern of results for producing absolute expressions from digital clocks showed a similar pattern, with naming latencies increasing for longer utterances.

To conclude, we obtained evidence for different levels of speech planning involved in clock time production. Furthermore, which levels of speech planning are engaged is mainly determined by expression format (absolute vs. relative) rather than by clock display (analog vs. digital).

SUMMARY AND CONCLUSIONS

CHAPTER 6

This thesis addressed the spoken production of complex numerals for time and space. So far, research conducted in the domain of numerical cognition has mainly focused on the production of relatively simple numerals like single- and two-digit numbers (cf. Brysbaert, 1995; Fias, Reynvoet, & Brysbaert, 2001). The production of complex numerical expressions like those involved in telling time (e.g., "quarter to four") or producing house numbers (e.g., "two hundred forty-five") has been almost completely ignored (except for a recent study on the production of clock time expressions, cf. Bock, Irwin, Davidson, & Levelt, 2003). Yet, adult speakers produce such expressions on a regular basis in everyday communication. Thus, no theory on numerical cognition or speech production is complete without an account of the production of multi-morphemic utterances such as complex numeral expressions.

The main question of this thesis is which particular speech planning levels are involved in the naming and reading of complex numerals for time and space. This issue was investigated by examining different modes of response (i.e. clock times vs. house numbers), different input formats (i.e., Arabic digit vs. alphabetic house numbers and clock times; analog vs. digital clock displays), and different expression types (i.e., relative vs. absolute time expressions).

PLANNING LEVELS IN NAMING AND READING COMPLEX NUMERALS

In Chapter 2, two experiments were reported in which speakers named (Experiment 1, Arabic digit format) or read aloud (Experiment 2, alphabetic format) complex numerals as house numbers and clock times. House number naming latencies were mostly determined by morphophonological factors such as whole-form and cumulative morpheme frequency and utterance length (number of phonemes). Likewise, house number reading latencies showed evidence of morphophonological planning factors with response latencies increasing monotonically with utterance length (number of morphemes), indicating seriality of speech planning. In contrast, clock time naming latencies (Arabic digit format, e.g., 2:45) revealed an additional conceptual involvement. When a speaker needs to produce a relative time expression, such as “quarter to three”, in response to a digital clock (i.e., 2:45), he first has to extract the hour (i.e., 2) and minute (i.e., 45) information from the input, and subsequently transform that information in order to determine the correct reference point (i.e., full hour, half hour, or coming hour) and distance in minutes (i.e., zero, five, ten, fifteen) from that reference point, before the corresponding lemmas (i.e., *quarter*, *to*, *three*) and word forms can be encoded for articulation. In contrast, when the same set of clock times were presented in alphabetic format (Experiment 2, e.g., KWART VOOR DRIE) such conceptual preparation would no longer be necessary, and hence reading latencies should show evidence of morphophonological planning factors only, as was empirically observed. Thus, it could be concluded that different planning levels are engaged in the naming (Arabic digit input format) and reading (alphabetic format) of complex numerals for time and space.

Chapter 3 reported two eye-tracking experiments in which gaze durations and response latencies were recorded while speakers named or read aloud complex numeral pairs as house numbers and clock times. The aim was to examine whether gaze durations would reflect the speech planning levels (from conceptual preparation to morphophonological encoding) that are involved in the naming and reading of complex numerals for time and space, as discussed in Chapter 2. Multiple regression analyses carried out on the data indicated that gaze durations were mainly determined by morphophonological planning factors (i.e., numeral length, logarithm of whole-form and cumulative morpheme frequency) for house number naming and reading. In contrast, gaze durations for clock time naming were in addition determined by conceptual level factors, such as determining the utterance referent (i.e., full hour, half hour, coming hour) and the distance in minutes. However, there was no evidence in gaze durations for such conceptual level involvement in the case of clock time reading. Furthermore, several dissociations were obtained between gaze durations and response latencies. This came down to response latencies being less sensitive to utterance length in speech planning than gaze durations, suggesting that speakers set different criteria for the onset of articulation and the shift of gaze. Note that this finding of response latencies showing less (in the case of clock times) or even no evidence (in the case of house numbers) of speech planning factors could be taken as a discrepancy with the previous findings reported in Chapter 2. However, in the present study the naming and reading of complex numeral *pairs* instead of *single* complex numerals was investigated, resulting in longer utterances to be generated by the speaker. Presumably, when long utterances have to be produced (pairs of complex numerals) a speaker carries out minimal advance speech planning before articulation initiation, and plans the rest of the utterance while speaking. This suggests that speakers adopt different criteria for articulation onset and shift of gaze for long utterances, both in naming and oral reading.

TELLING TIME FROM ANALOG AND DIGITAL CLOCKS

The second part of the thesis (Chapters 4 and 5) followed up on the finding of conceptual level speech planning in the case of clock time naming (reported in Chapters 2 and 3). More specifically, the research was aimed at characterizing the conceptual transformations of determining the utterance referent and the distance in minutes. It assessed whether such conceptual transformations are shared between telling time from different clock displays (i.e., analog versus digital clocks) and different time expressions (i.e., relative versus absolute).

In Chapter 4, a priming study was reported that investigated the interplay of the conceptual operations on the minute and hour information required for producing relative time expressions (e.g., “quarter to three”) for different clock displays. Speakers told the time from an analog clock (the prime) directly before telling time from a digital clock (the target). Targets referred to three utterance referents: the full hour (e.g., 2:00), the half hour (e.g., 2:30), or to the coming hour (e.g., 2:45). Primes differed from targets both on the hour and minute dimension:

They were either one or two hours and five or ten minutes later than the targets. In this way, there would be no visual or speech output overlap between prime and target. Hence, any effects on target naming latencies due to the preceding prime could be attributed to an overlap in conceptual operations. Digital naming latencies were shorter with a five-minute than with a ten-minute difference between prime and target, whereas the differences in hour had no effect. Furthermore, the distance in minutes only had an effect when the target utterances made reference to the half hour and the coming hour, but not when reference was made to the full hour. This suggests that determining the reference point is accomplished in a different way, whereas (once the reference point and absolute minutes have been determined) determining the minutes relative to the reference point has certain aspects in common for telling time from analog and digital clocks. To summarize, these findings suggest that conceptual transformations are shared between telling time from analog and digital clocks.

Given that conceptual operations are to some extent shared for producing relative expressions from analog and digital clocks, Chapter 5 addressed the question whether similar speech planning processes (from conceptual preparation to morphophonological encoding) are engaged when time is told using different expression formats. Speakers produced relative time expressions (e.g., "quarter to three") to analog and digital clocks. In addition, they produced absolute time expressions (e.g., "two forty-five") to digital clocks. Overall, we observed that producing absolute expressions from digital clocks was achieved the quickest, followed by producing relative time expressions from digital clocks, and finally producing relative time expressions from analog clocks. Whereas for producing absolute time expressions from digital clocks it suffices to read aloud the digits in a left-to-right manner, for producing relative time expressions the mapping of minute and hour information onto the utterance is less straightforward (e.g., 20 in the digital input becomes "ten" in the utterance). Hence, naming latencies showed evidence of a similar conceptual involvement, along with morphophonological planning, when relative time expressions had to be produced from either analog or digital clocks. In contrast, naming latencies were determined by morphophonological planning factors only when absolute time expressions had to be produced from digital clocks.

Taken together, the findings from Chapters 4 and 5 indicate that different levels of speech planning (from conceptual preparation to morphophonological encoding) are engaged when time expressions are produced. More specifically, the level of speech planning is dependent on the particular expression format used to produce such time expressions (absolute vs. relative), rather than on clock display (analog versus digital clocks).

DISCUSSION

This thesis incorporated different experiments in the domain of complex numeral production. As such, this research brings together the experimental fields of speech production and numerical cognition. In the next section, some implications of the current findings with respect to theories of speech production and numerical cognition are discussed.

SPEECH PRODUCTION

Complex numeral production entails the production of multi-morphemic utterances (e.g., “kwart voor vier”, English “quarter to four”). The experiments reported in this thesis suggested that producing these multi-morphemic numerals involves the same planning levels as engaged in single word production (Levelt, Roelofs, & Meyer, 1999).

Moreover, evidence was obtained for left-to-right seriality in planning these multi-morphemic utterances. Complex numerals that resulted in longer utterances (e.g., “tweehonderdvijfentwintig”, English “two hundred twenty-five”) were significantly produced slower and looked at longer than shorter utterances (e.g., “tweehonderdtwintig”, English “two hundred twenty”). This suggests that speakers start planning a complex numeral in a left-to-right fashion, resulting in utterance length effects on response latencies and gaze durations.

However, the experiments reported in Chapter 3, in which pairs of complex numerals had to be produced, showed that response latencies and gaze durations do not always point in the same direction. That is, whereas gaze durations showed evidence of utterance length in naming and reading of complex numerals for time and space, response latencies did not. Since the amount of speech to be generated was greater for these numeral pairs (e.g., “two hundred forty-five and three hundred) than for producing single complex numerals, this outcome suggests that speakers adopted different criteria for articulation initiation and shift of gaze. In other words, when much needs to be said, a speaker may choose to initiate articulation early, and plan the rest of the upcoming utterance while speaking, in order to remain fluent.

NUMERICAL COGNITION

In all experiments reported in this thesis, no evidence was found for the conceptual factor of magnitude playing a role in producing complex numerals. The magnitude of the whole three-digit numeral did not make a significant contribution to response latencies (Chapter 2) and gaze durations (Chapter 3) for house number naming. If magnitude had played a role in naming complex numerals from Arabic digit format, there should have been a steady increase in response latencies and gaze durations from complex numerals ending on 00 to 55, the so-called magnitude effect (Brysbaert, 1995). Instead, a typical zigzag pattern was obtained, for response latencies and gaze durations alike, with increasing latencies for the longer numerals ending on 5 compared to shorter numerals ending on 0. This finding suggests that both response latencies and gaze durations for the production of complex numerals as house numbers were mainly determined by utterance length, rather than by magnitude of the 3-digit number.

However, note that I also assessed the magnitude of the last two digits comprising the complex numerals in Chapter 2, and could not find any evidence of a magnitude effect either. This was surprising, since magnitude effects have been frequently reported for two-digit numerals (Dehaene, 1992; Fias, 2001). Importantly, such magnitude effects have mainly been reported in tasks in which Arabic numerals have to be encoded conceptually for cognitive manipulation or quantitative comparisons (cf. Cipolotti & Butterworth, 1995). Since the magnitude of the complex numerals or its last two digits per se was not needed for successful task completion (the digits in the input could be directly mapped onto the corresponding lemmas in the slots in the house number utterance to be named), magnitude did not play a role here.

CONCLUDING REMARKS

In summary, complex numeral expressions are widely used in everyday conversation. They constitute a separate class of multi-morphemic utterances. Nevertheless, the experiments reported in this thesis have shown that similar speech planning levels are involved as in single word production. Furthermore, complex numeral expressions are planned in a rightward serial fashion, just like single words and multiple object phrases. Finally, the levels of speech planning engaged in complex numeral production can be selectively modulated by response mode (house number versus clock time), input format (Arabic digit versus alphabetic; analog versus digital clocks) and expression format (relative versus absolute time expressions).

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SAMENVATTING

Meercijferige getallen spelen een belangrijke rol in onze dagelijkse communicatie. De combinatie van twee of meer cijfers kan verschillende soorten informatie weergeven, zoals telefoonnummers, postcodes, geboortedata, huisnummers, kloktijden etc. De linguïstische expressies, die vervolgens geproduceerd worden om die verschillende typen informatie over te brengen, zijn zeer divers, en hebben welomschreven syntactische structuren. In het Nederlands is het bijvoorbeeld gebruikelijk een postcode in paren uit te spreken (bijv. de postcode 6581 HW als: "vijfenzestig-eenentachtig-HW), terwijl de getallen in een telefoonnummer bijna allemaal als afzonderlijke getallen worden opgelezen (bijv. het telefoonnummer 024-3881295 wordt uitgesproken als: "nul-vierentwintig-drie-acht-acht-een-twee-negen-vijf"). Er zijn grote verschillen tussen talen in de conventies over hoe dergelijke meercijferige getallen dienen te worden uitgesproken (zo wordt de kloktijd 13:30 in het Nederlands als "half twee" uitgesproken, maar in het Engels als "one thirty", letterlijk "een uur dertig").

Dit proefschrift beschrijft onderzoek naar het benoemen van driecijferige getallen. De vraag die centraal staat is welke niveau's van spraakvoorbereiding betrokken zijn bij de productie van complexe numerieke expressies. Voordat een driecijferig getal geproduceerd kan worden moet de spreker eerst de conceptuele boodschap bepalen die hij wil overbrengen (conceptuele voorbereiding) alvorens de individuele constituenten geselecteerd (lemmaselectie), de woordvormen geactiveerd (vormencodering), en uitgesproken kunnen worden. Deze vraagstelling omtrent de verschillende niveau's van spraakplanning werd onderzocht door twee cognitieve domeinen met elkaar te vergelijken, namelijk die van *tijd* en *ruimte*. Hetzelfde driecijferige getal, zoals bijvoorbeeld 230, kan tegelijkertijd de dimensie van tijd (de kloktijd "half drie") en de dimensie van ruimte (het huisnummer "tweehonderddertig") representeren. Tevens werd de invloed van *weergaveformaat* (bijv. huisnummers weergegeven in Arabische cijfers 230 of uitgeschreven in alfabetisch formaat TWEEHONDERDDERTIG) en *uitingsvorm* (bijv. kloktijden uitgesproken op de absolute "twee uur dertig" versus de relatieve "half drie" manier) op het spraakvoorbereidingsproces onderzocht. Hieronder volgt een beknopte samenvatting van de bevindingen per hoofdstuk.

In Hoofdstuk 2 worden twee experimenten beschreven die als primair doel hadden de verschillende stadia van spraakvoorbereiding, die betrokken zijn bij de productie van driecijferige getallen, in kaart te brengen. Sprekers produceerden een reeks driecijferige getallen, lopend van 200 tot en met 955 in stappen van 5, als huisnummers en als kloktijden. Tevens werd er gekeken naar de invloed van weergaveformaat op het spraakvoorbereidingsproces. De driecijferige getallen werden gepresenteerd als Arabische cijfers (bijv. 245 en 2:45, Experiment 1) of alfabetisch (bijv. TWEEHONDERDVIJFENVEERTIG en KWART VOOR DRIE, Experiment 2). Zowel voor het benoemen als voor het hardoplezen van huisnummers (een spreker reageerde bijvoorbeeld met "op tweehonderdvijfenveertig") werd er evidentie gevonden voor de invloed van morfofonologische factoren op de spraakplanning. Sprekers begonnen later met benoemen en hardoplezen wanneer het een relatief lange (gemeten in aantal fonemen en morfemen) huisnummerexpressie betrof en naarmate de uiting minder frequent voorkwam. Deze bevindingen kunnen worden gezien als een bevestiging van het theoretische standpunt uit de taalproductie-literatuur (zie Levelt, Roelofs, & Meyer, 1999) dat spraakvoorbereiding, meer specifiek het stadium van vormencodering, op een seriële manier verloopt, dat wil zeggen van links naar rechts. Bovendien blijkt uit deze resultaten dat dit serialiteitsprincipe niet alleen voor het benoemen van huisnummers in Arabisch cijferformaat opgaat, maar ook voor het hardoplezen in alfabetisch formaat. Bij het benoemen en hardoplezen van kloktijden bleken eveneens morfofonologische factoren een rol te spelen bij de spraakvoorbereiding. Maar anders dan voor huisnummers werd er voor het benoemen van kloktijden ook evidentie gevonden voor een invloed van conceptuele factoren. In Experiment 1, waarin sprekers kloktijden (variërend van 2:00 to 9:55 in stappen van 5) gepresenteerd in Arabisch cijferformaat benoemden (bijv. 2:45 als "om kwart voor drie"), weerspiegelden de benoemingstijden de conceptuele operaties die noodzakelijk zijn voor het bepalen van de uit te drukken tijdsinformatie. Het stadium van conceptuele preparatie kan worden geïllustreerd aan de hand van een voorbeeld. Wanneer een spreker "om kwart voor drie" moet produceren als respons op de digitale kloktijd 2:45, moet eerst de uitingsreferent bepaald worden (in dit geval is dat *drie uur*), samen met de afstand in minuten (in dit geval *vijftien*), alvorens de corresponderende lemmata (*kwart*, *voor*, en *drie*) en woordvormen geselecteerd kunnen worden. Interessant is dat beide typen informatie niet direct afgeleid kunnen worden uit de digitale weergave, maar dus conceptueel bepaald moeten worden (door 45 te transformeren in 15, en 1 uur op te tellen bij 2). Echter, wanneer dezelfde kloktijden werden aangeboden in alfabetisch formaat (Experiment 2), en hardop moesten worden gelezen, werden de responstijden slechts nog beïnvloed door morfofonologische factoren, zoals al eerder werd gevonden voor de huisnummers. Kortom, de studies in Hoofdstuk 2 lieten zien dat verschillende niveau's van spraakvoorbereiding (conceptuele preparatie tot en met vormencodering) betrokken zijn bij het benoemen en hardoplezen van driecijferige getallen. Verder bleek dat welke stadia van spraakplanning precies betrokken zijn bij de productie van kloktijden afhing van weergaveformaat.

Hoofdstuk 3 bespreekt twee oogbewegingsstudies die de planningsprocessen bij de productie van driecijferige getallen verder onderzochten. Nu betrof het echter de vraag of de kijkduren (d.w.z. hoe lang een spreker naar een uit te spreken driecijferig getal blijft kijken) een vergelijkbaar patroon zouden laten zien wat betreft spraakplanningsstadia (van conceptuele preparatie tot en met vormencodering) als de responstijden. Als dit niet het geval is, dan zou dit er bijvoorbeeld op kunnen duiden dat sprekers al beginnen te articuleren terwijl ze ondertussen nog bezig zijn met het voorbereiden van de rest van de uiting (het is bekend dat het voorbereiden van spraak veel minder tijd kost dan het daadwerkelijk uitspreken). Sprekers benoemden (Experiment 1) en lazen hardop (Experiment 2) paren van driecijferige getallen als huisnummers en als kloktijden. Ze zeiden bijvoorbeeld "op tweehonderdvijfendertig en vierhonderdvijftien" voor de huisnummers of "om vijf over half drie en kwart over vier" voor de kloktijden. Gemeten werd het moment waarop ze begonnen met spreken en hoelang er werd gekeken naar het eerst te benoemen driecijferig getal in het paar. De techniek van multiple regressie werd toegepast op de data en liet zien dat de kijkduren voor het benoemen en hardoplezen van de huisnummers voornamelijk bepaald werden door morfofonologische planningsfactoren (zoals uitingslengte en frequentie). In contrast daarmee lieten de kijkduren voor het benoemen van kloktijden, maar niet voor het hardoplezen, naast morfofonologische planning duidelijk evidentie zien van conceptuele voorbereiding. Deze bevindingen zijn een replicatie van de eerder gevonden resultaten zoals gerapporteerd in Hoofdstuk 2. De responstijden voor het benoemen en hardoplezen van de driecijferige getalsparen werden echter in mindere mate (of helemaal niet) beïnvloed door conceptuele en morfofonologische spraakplanningsfactoren. Blijkbaar kozen sprekers ervoor een minimale hoeveelheid van de uiting vooruit te plannen voordat ze begonnen met het benoemen en hardoplezen van de driecijferige getalsparen. Een dergelijke bevinding kan worden opgevat als een indicatie van *incrementaliteit* (d.w.z. dat spraakplanning en articulatie in de tijd overlappen).

Het tweede deel van dit proefschrift (Hoofdstuk 4 en 5) gaat dieper in op de bevinding van conceptuele spraakvoorbereiding bij het benoemen van kloktijden (zoals gerapporteerd in Hoofdstuk 2 en 3). Het onderzoek was erop gericht meer inzicht te krijgen in de conceptuele component (het bepalen van de uitingsreferent en de afstand in minuten) die betrokken is bij klokbenoemen. Meer specifiek betrof het de vraag of conceptuele preparatie eveneens noodzakelijk is voor klokbenoemen wanneer tijd wordt afgelezen van verschillende typen klokken (analoog versus digitaal) of wanneer verschillende uitingsvormen (relatieve versus absolute tijdsexpressies) worden gebruikt.

In Hoofdstuk 4 wordt verslag gedaan van een priming-studie waarin de invloed van klokweergave werd onderzocht op de conceptuele operaties die een spreker moet uitvoeren om tijd op een relatieve manier uit te drukken. Sprekers produceerden relatieve tijdsexpressies (bijv. “kwart voor drie”) van een analoge klok (de “prime”) vlak voordat ze de tijd oplazen van een digitale klok (de “target”). Beide klokken gaven nooit dezelfde tijd aan. De analoge klokken lieten tijden zien die ofwel 1 of 2 uur, en 5 of 10 minuten later waren dan de digitale klokken. De digitale klokken konden worden ingedeeld op basis van uitingsreferent: (1) het hele uur (bijv. 2:00), (2) het halve uur (bijv. 2:30), en (3) het komende uur (bijv. 2:45). De benoemingslatenties voor de digitale klokken werden gemeten. De vraag die nu vervolgens beantwoord kon worden was of de benoeminglatenties voor de digitale klokken beïnvloed zouden worden door de voorafgaande benoeming van een analoge klok (als gevolg van een overlap in conceptuele voorbereiding). En zo ja, of dit effect dan hetzelfde zou zijn voor de verschillende uitingsreferenten of niet. De benoemingslatenties waren korter wanneer de voorafgaande prime 5 in plaats van 10 minuten later was dan de target, maar het verschil in uren (1 of 2) had geen effect. De verschillende manieren waarop de uitingsreferent door een spreker moet worden bepaald van een analoge (de spatiële positie van de kleine wijzer) en een digitale klok (transformatie van getallen) liggen wellicht aan de geobserveerde afwezigheid van een uren-effect op de benoemingslatenties ten grondslag. Verder was het minuten-priming effect alleen aanwezig voor de benoeming van digitale klokken die het halve en het komende uur als uitingsreferent hadden, maar niet het hele uur. Merk op dat juist voor die laatste categorie van het hele uur geen conceptuele operaties nodig zijn voor het produceren van een relatieve tijdsexpressie van een digitale klok—2:00 kan direct worden opgelezen als “twee uur”. Dit zou een verklaring kunnen zijn voor de afwezigheid van een minuten-priming effect voor de digitale klokken die het hele uur aangaven. Kortom, deze studie liet zien dat bepaalde aspecten van conceptuele voorbereiding gedeeld zijn voor het produceren van relatieve tijdsexpressies van analoge en digitale klokken.

In hoeverre spraakvoorbereidingsprocessen vergelijkbaar zijn voor de productie van verschillende tijdsexpressies (relatief of absoluut) werd nader onderzocht in Hoofdstuk 5. Sprekers produceerden relatieve tijdsexpressies (“kwart voor drie”) in reactie op analoge en digitale klokken. Bovendien produceerden dezelfde sprekers absolute tijdsexpressies ("twee uur vijfenveertig") in respons op digitale klokken. In het algemeen werden absolute tijdsexpressies in respons op digitale klokken het snelst geproduceerd, respectievelijk gevolgd door relatieve expressies in reactie op digitale en analoge klokken. Wanneer een spreker de tijd van een digitale klok op een absolute manier leest, is het alleen noodzakelijk de getallen uit de digitale invoer van links naar rechts op te noemen. Voor het produceren van relatieve tijdsuitingen zijn veelal transformaties van de getallen in de invoer nodig voordat de juiste expressie geproduceerd kan worden. Dit zou het verschil in snelheid tussen de drie condities kunnen verklaren. Verder lieten analyses van de data zien dat de benoemingstijden voor relatieve tijdsexpressies van digitale en analoge klokken werden bepaald door zowel conceptuele als morfofonologische voorbereiding, terwijl de benoemingstijden voor de absolute tijdsexpressies van digitale klokken alleen evidentie toonden voor morfofonologische planningsfactoren. Deze resultaten ondersteunen de vorige studie in Hoofdstuk 4, waarin werd aangetoond dat aspecten van spraakvoorbereiding vergelijkbaar zijn voor het produceren van relatieve tijdsexpressies in reactie op analoge en digitale klokken. Kortom, welke stadia van spraakvoorbereiding betrokken zijn bij het produceren van tijdsexpressies wordt met name bepaald door de uitingsvorm (relatief of absoluut) die door een spreker wordt gekozen, en in mindere mate door klokweergave (analoog of digitaal).

Tot slot, de cartoon aan het begin van dit proefschrift illustreert dat meercijferige getallen verschillende soorten informatie kunnen weergeven. De reden dat we daar niet altijd bij stil staan is waarschijnlijk dat in de dagelijkse communicatie de juiste context voor de interpretatie van meercijferige getallen (is het een kloktijd of een huisnummer?) meestal verschaft wordt.

CURRICULUM VITAE

Marjolein Meeuwissen werd geboren in Heerlen op 20 juli 1978. Na het behalen van haar Gymnasium-diploma in 1996 aan het Bernardinuscollege te Heerlen studeerde zij Psychologie aan de Universiteit Maastricht. Haar scriptie-onderzoek deed ze gedurende zes maanden op het lab van Prof. Marta Kutas aan de University of California San Diego, Verenigde Staten. In december 2000 werd haar een stipendium toegekend door de Max Planck Gesellschaft zur Förderung der Wissenschaften om promotie-onderzoek te doen aan het MPI binnen de Utterance Encoding Group. Vanaf september 2004 is zij werkzaam als postdoctoraal-onderzoeker op het lab van Prof. Kay Bock aan het Beckman Institute for Advanced Science and Technology in Illinois, Verenigde Staten. Haar verblijf wordt gefinancierd door middel van een TALENT-beurs die aan haar werd toegekend door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

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