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Human Aging and Duration Judgments: A Meta-Analytic Review

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Differences in duration judgments made by younger and older adults were reviewed. Previous research is unclear about whether such differences exist and, if so, how they may be explained. The meta-analyses revealed substantial age-related differences. Older adults gave larger verbal estimates and made shorter productions of duration than did younger adults. There were no age-related differences in reproduction of duration or in psychophysical slope relating judged and target duration. Older adults' duration estimates were more variable than were those of younger ones. Findings are discussed in terms of pacemaker rate and attentional resources. An explanation regarding divided attention between nontemporal and temporal information processing best explains the findings.

Various cognitive processes change as a person ages. The slowing of information processing may be "the earliest, and most marked, symptom of cognitive aging" (Wearden, Wearden, & Rabbitt, 1997, p. 962). Aging appears to be accompanied by a slowing of the component processes of many cognitive tasks, such as those that heavily involve working memory (Light, 1991; Salthouse, 1991), explicit memory retrieval (Craik & Jennings, 1992; Light, 1991), and divided attention (Salthouse, Rogan, & Prill, 1984). There are conflicting theories on why age-related slowing may occur (Kausler, 1991). Slower processing speed and memory limitations may result from a reduction in general processing resources (Salthouse, 1994). Salthouse (1996) proposed some generalizations about cognitive aging, three of which are as follows:

1. Diverse cognitive variables reveal age-related differences. This implies that either many specific factors or a few general factors influence age-related differences.
2. Age-related influences on various cognitive variables are correlated. Furthermore, unique age-related influences are few and small. This implies that general factors must be postulated to account for the shared influences.
3. The speed of performance of simple cognitive tasks shares considerable age-related variance with many cognitive variables. This implies that factors related to simple processing speed or efficiency must be included in any explanation.

For reasons we now explain, these generalizations suggest that older adults may differ from younger adults in timing and judging durations. Consider research and theories on this issue, which form the primary focus of our work.

Psychological Time and Aging

Psychological time has been an important topic of research and theorizing for more than a century (Block, 1990; Michon & Jackson, 1985), perhaps because timing is essential to the optimal functioning of organisms. Psychological time involves processes by which an organism adapts to and represents the temporal properties of environmental events and relationships among them. Timing of durations ranging from seconds to minutes is essential for representing the immediate external environment. For example, while driving a vehicle or crossing a busy street, speed and time estimates provide vital information (Manser & Hancock, 1996). Many everyday behaviors involve short duration estimation, and it is important to understand the underlying processes and whether there are individual differences in them. Consequently, understanding how timing processes vary as a function of age is an important issue in its own right.

Beginning with early essays on the psychology of time (Guyau, 1890/1988; Janet, 1877), several theorists have focused on the experience of duration. Early researchers have studied duration judgments for their intrinsic interest, such as in the context of psychophysical investigations (see Woodrow,

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1951). More recently, and arguably of more importance, researchers study duration judgment processes to clarify more general physiological, memorial, and attentional processes. Here we also focus on duration judgments.

Early theorists speculated about possible differences in duration judgments between younger and older adults. Janet (1877) proposed that the ratio between a duration and a person's age influences the person's duration judgments. James (1890) claimed that "the same space of time seems shorter as we grow older," but he qualified this by saying "that is, the days, the months, and the years do so; whether the hours do so is doubtful, and the minutes and seconds to all appearances remain the same" (p. 284). Mach (1900) also thought that the physiological unit of time lengthened with age. A controversy ensued after the publication of an article by Nitardy (1943) that essentially echoed these previous comments. Authors of nine additional short articles (e.g., Carlson, 1943) replied to Nitardy, but they provided no empirical data. Older adults do indeed report that time passes quickly (Baum, Boxley, & Sokolowski, 1984) and at a faster rate than when they were younger (Schroots & Birren, 1990). Research using questionnaires tends to support this view (Joubert, 1983; Lemlich, 1975; Walker, 1977).

Cohen (1967) speculated about why the years seem to pass more quickly as a person ages. He attributed this, in part, to a slower metabolic rate. He thought this slowing would have an effect on duration judgments similar to the hypothetical effect of reduced body temperature, that is, subjective time would decrease and the calendar year would seem shorter. Fraisse (1957/1963) suggested that "decreased biological activity may make us register fewer changes" (p. 248), thereby leading to an apparent speeding in the rate of physical time. However, he cautioned that older adults may compensate for any such influences, claiming (on the basis of little evidence) that there is "hardly any change in their objective time judgments" (Fraisse, 1957/1963, p. 248). Whitrow (1972) also proposed that "our sense of temporal duration . . . depends on our age, for our organic processes tend to slow down as we grow older, so that, compared with them, physical time appears to go faster" (p. 43). More recently, Craik and Hay (in press) also suggested that the reason why older adults perceive time as passing at a relatively fast rate is that a biological clock slows progressively as a person ages. The slowing of a biological clock would presumably give rise to the feeling that external time passes faster.

Experiments comparing the magnitude of duration judgments made by older and younger adults date from the late 1950s (Feifel, 1957; Goldstone, Boardman, & Lhamon, 1958). Nevertheless, we know of no systematic description or understanding of age-related differences in duration judgments that has emerged, and we know of no comprehensive and recent review of experimental findings that has been published.

Models of Duration Judgment Processes

Theorists have proposed several kinds of models to explain duration judgments (Block, 1990). One kind emphasizes physiological mechanisms. In the most common variant, an internal clock, consisting of a pacemaker, an accumulator, a reference memory, and other components, subserves time-related behavior (Wearden & Penton-Voak, 1995). The pacemaker rate may be influenced by biological variables such as metabolism and brain temperature, neurotransmitter receptor sites, psychoactive drugs, and arousal level. Because basal metabolism and brain temperature decrease as a person ages (Altman & Dittmer, 1968; Kadlub, 1996), the pacemaker rate may also decrease. A person may compensate continuously (recalibrate) for this hypothetical slowing, however, by changing the contents of the reference memory store, so that fewer pacemaker-produced pulses are needed to correspond to a learned duration unit (such as 1 min).

Another kind of model proposes that duration is a cognitive construction that is influenced by attention and memory processes (Block, 1990). Several kinds of methodological and individual factors may influence duration judgments because of their effects on attention and memory (Block, 1985, 1989, 1990).

In light of these possibilities, the choice of a method to investigate age-related differences in duration judgments may be critical. Whether duration judgments show any age-related differences may depend on the specific methodology used to obtain them.

Methodological Factors

Duration Judgment Paradigm

One important variable influencing duration judgments is whether a person knows in advance that a duration estimate will be required. In the prospective paradigm, a person has this knowledge; in the retrospective paradigm, a person does not. The magnitude and interindividual variability of duration judgments depend critically on this difference in duration judgment paradigm (Block & Zakay, 1997). However, we were not able to assess age-related differences in retrospective duration judgments or investigate duration judgment paradigm as a moderator variable. The only articles we know of using the retrospective paradigm revealed methodological problems (Kelley, 1980) or contained insufficient statistics (Vanneste & Pouthas, 1995) and yielded no data relevant to our meta-analyses.

Duration Judgment Method

Another important variable is the method used to obtain duration judgments. Researchers typically use one of three main methods: verbal estimation, production, and reproduction. These methods entail somewhat different cognitive processes, and the resulting duration judgments reveal characteristics of those processes (Zakay, 1990, 1993; Zakay & Block, 1997).

The methods of verbal estimation and production involve comparing duration experience with internal (reference memory) information concerning conventional duration units such as seconds and minutes. In the method of verbal estimation, a person experiences a target duration and then must translate his or her experience of it into an estimate in clock units, usually seconds. This translation introduces variability into the judgments because different people have learned to accomplish this with different proficiency. In the method of production, a person attempts to delimit an objectively measured duration corresponding to a verbally stated time period (e.g., "Say *stop* after what seems like 60 s to you"). As with verbal estimates, this kind of judgment requires a translation, but in this case it is in the reverse direction (i.e., from an objectively labeled duration to a subjectively experienced duration). In a variant on this method, the method of repeated production, a person delimits several objectively labeled durations of a specified length, usually 1 s (e.g., "Press this button once every second until I tell you to stop"). Verbal estimation and production methods have drawbacks in some experimental contexts because of the need to assume that the translation between conventional units and experienced duration is reliable. These methods, however, may be suitable to investigate individual differences (or effects of variables that may influence the rate of internal processes). Researchers have successfully used them in studies of manipulations thought to influence the rate of internal time-keeping processes, such as drugs (e.g., Frankenhaeuser, 1959; R. E. Hicks, 1992). However, if internal clock or time-keeping processes change gradually with age, a person may use feedback to recalibrate internal time keeping against physical units of duration (Surwillo, 1968).

The method of reproduction does not involve verbally stated units. A person experiences a target duration and then attempts to delimit another time period that is the same length. This method, which relies on a comparison of experiences instead of on conventional duration units, has the potential drawback that reproductions may be "an index only of the consistency of the subjective time base; [they provide] no information as to the rate itself" (Cahoon, 1969, p. 261). Even if the rate of physiological and cognitive processes varies with age, the same rate will subserve a person's experiencing the target duration and reproducing it. Thus, the reproduction method may detect individual differences only if it is used in the framework of psychophysical studies, in which duration is varied. In addition, judgments obtained by using the reproduction method (as well as the production method) may be confounded by extraneous variables such as the desire to terminate the experiment sooner, impatience, or the inability to delay a response.

Age-Related Differences

Individual differences in duration judgments may originate in various physiological parameters and cognitive processes, including (a) the rate of biological processes, such as those thought to underlie an internal pacemaker; (b) the basal metabolic rate or brain temperature, perhaps by influencing the pacemaker rate; (c) the strength, clarity, duration, or variability of memory processes, such as those that mediate the encoding of information during a duration; and (d) attentional resources or resource allocation, especially involving attention to time. In our review, we focus mainly on the two hypotheses that relate most directly to the available evidence: the pacemaker-rate hypothesis and the attention hypothesis. (Later, we also discuss the metabolism or temperature hypothesis and the memory hypothesis.) An attentional-gate model (Zakay & Block, 1997), which combines pacemaker and attentional components in an integrated model, emphasizes that duration timing may require a person to divide attention between nontemporal (stimulus) information processing and temporal information processing. The magnitude of prospective duration judgments is mainly influenced by the amount of attention a person allocates to processing temporal information. The attentional-gate model can account for much of the evidence (Zakay & Block, 1997).

Assuming that there is an age-related slowing of a pacemaker rate, a decrease in attentional resources, or both, there are two possible scenarios, neither of which is currently supported by evidence. First, older adults may learn to compensate for the slowed pacemaker or decreased resources. In this scenario, one expects no age-related difference in duration judgments. Alternatively, older adults may not sufficiently recalibrate or compensate for the slowed pacemaker or decreased resources. In this scenario, older adults will give smaller verbal estimates and make longer productions of durations than will younger adults. However, an age-related difference in pacemaker rate or attentional resources should not influence reproductions because the method of reproduction involves a comparison of durations (the standard, or target, duration and the comparison, or reproduced, duration). Thus, both pacemaker and attentional models (e.g., Zakay & Block, 1997) predict that duration judgment method will be an important moderator of age-related differences in duration judgments, if any difference is found.

One crucial distinction between pacemaker and attentional hypotheses is that pacemakers are assumed to operate fairly autonomously, perhaps being influenced by biological variables but not by cognitive factors. However, attentional models make specific predictions concerning cognitive factors such as information-processing difficulty. Prospective duration timing requires a person to divide attention between nontemporal (stimulus) information processing and temporal information processing (Brown, 1997; Zakay & Block, 1997). Researchers have not yet found the exact nature of the cognitive processes that occur when a person is said to attend to time. Indeed, such processes may vary depending on the person and the situation (e.g., duration judgment method). Attending to time may involve judging the recency of the signal that indicated the start of a time period, engaging in chronometric counting, imagining events signaling the end of a time period, or a combination of these and other such processes. Although research has indicated that attending to temporal information and attending to nontemporal information compete for general attentional resources, the extent to which this implies a working-memory limitation, or a limited capacity within some functional subsystem of working memory, remains unclear. The attentional-gate model of prospective duration judgment somewhat clarifies the notion of attending to time (Zakay & Block, 1997). In this model, attending to time means focusing on the stream of signals produced by a pacemaker and transferring a representation of the total number of signals to a working-memory store. Thus, if a person allocates relatively more attention to time, more signals are included in the working-memory representation, and the expected result is that a person will give relatively larger verbal estimates and make relatively shorter productions of duration.

Duration judgment evidence may therefore test the notion that divided-attention tasks affect older adults in a relatively severe way, whereas tasks not requiring divided attention may not affect older adults any more than they do younger adults. If this were the case, attentional models predict that the difficulty of the nontemporal information-processing task will moderate any age-related effect on prospective duration judgments (cf. Craik & Hay, in press). There may be little or no age-related difference if the primary (nontemporal) task is easy. However, as nontemporal task difficulty increases, older adults may accumulate relatively less temporal information than would younger adults. The consequences of this on duration judgment magnitude will depend on the specific method used. If the primary (nontemporal) task is more difficult, younger adults may still have enough attentional resources to allocate to the secondary (temporal) task, but older adults may have relatively few residual resources. As a result, older adults would give relatively smaller verbal estimates and make relatively longer productions. The effect on reproductions would depend on whether the target duration and the reproduction duration are filled with equally difficult tasks. If they are, no age-related difference is expected; if, instead, the target duration is filled with a difficult task and the reproduction duration is empty (as is usually the case), older adults' reproductions should be relatively short (just as their verbal estimates are smaller). In summary, studying age-related differences in duration timing may provide crucial converging evidence on the impact of aging on cognitive processes, such as those involving attention and working memory.

Specific Goals of the Present Meta-Analyses

The goal of our meta-analytic review was to evaluate evidence on age-related differences in human duration judgments while also discovering what variables (e.g., duration judgment method) moderate any obtained differences. The outcome may clarify or suggest theories concerning processes that produce age-related differences. The finding of moderator variables is vital information that clarifies proposed models. (In a meta-analysis, the finding of a moderator variable is analogous to the finding of an interaction effect in primary research.) Studies investigating duration judgments almost always report the duration length used, so we also accumulated primary-level statistics based on a common scale of measurement, the ratio of subjective to objective duration. In this regard, the present review differs from most meta-analytic reviews: The primary-level statistics clarify the meta-analytic statistics.

Several articles on age-related differences contain data on the interindividual variability of duration judgments, such as standard deviations. (None reported any data on intraindividual variability, another potentially interesting measure.) In spite of this, we know of no researchers who reported inferential statistics on variability data, and few commented on differences in variability. Because interindividual variability is theoretically relevant, we reviewed these data. Thus, the present meta-analysis reveals new information about interindividual variability in duration judgments, thereby suggesting whether different participants use similar or different kinds of processes (Wearden et al., 1997). Greater interindividual variability is expected if different participants use different processes and these processes affect duration judgments differently. It may also be expected if different participants use the same (or similar) processes, but the intraindividual variability of those processes differs (especially if only a few duration judgments are obtained).

Finally, we evaluated several studies in which the slope of the psychophysical or regression function relating subjective and objective duration was reported. These data may provide a relatively direct measure of hypothetical changes in the rate of an internal pacemaker because if the pacemaker rate decreases (and there is no compensation for this change), the psychophysical slope may also decrease. In other words, age and duration length may interact to influence duration judgments.

In summary, in our meta-analytic review we examined evidence for age-related changes in the magnitude and variability of duration judgments. Second, we clarified theories on changes observed in cognitive aging. Finally, we addressed the general issue of individual differences in temporal experience and judgment, which remains one of the most intriguing and poorly explained issues in the psychology of time.

Method

Sample of Studies

We searched a database containing more than 9,000 references on the psychology of time (Block & Eisler, 1998). It includes articles from the following sources: *Psychological Abstracts* (1923–1966) and *PsycINFO* (1967–1997), using the keywords *time perception* and *time estimation*; and *Medline* (1966–1997), using the keyword *time perception*.[1] It also includes references from published bibliographies on time research; references from articles, books, and book chapters; and references from our files (see Block & Zakay, 1997). We also searched *Social Sciences Citation Index* (Social SciSearch, 1977–1997) for articles that cited major articles, such as those by LeBlanc (1966, 1969). Finally, we checked the reference lists of all relevant studies.

To be included in our meta-analyses, an experimenter must have studied normal human participants of diverse ages, and a published article must have contained quantitative data on duration judgment magnitude in more than one age category (young adult, middle-age adult, and old adult). We compared younger adults and older adults, for whom younger and older participants' ages were coded variables. This process necessarily excluded any study in which age varied only within the narrow range of a single category (e.g., Fitzpatrick & Donovan, 1978; Grossman & Hallenbeck, 1965; Mentzer & Schorr, 1986; Newman & Gaudiano, 1984). It also excluded any study in which researchers did not obtain and report duration judgment magnitude, specifically (a) studies in which no experimental duration was presented or estimated, including those obtaining only questionnaire data (e.g., Baum et al., 1984; Gallant, Fidler, & Dawson, 1991; Joubert, 1983; Kuhlen & Monge, 1968; Lemlich, 1975; Walker, 1977); (b) experiments in which participants judged other temporal dimensions, such as recency, or lag (e.g., McCormack, 1982); (c) experiments in which participants received feedback on their judgments, thereby learning to make them more accurate (e.g., Arenberg, 1968; Lejeune & Pouthas, 1991; Rammsayer, Lima, & Vogel, 1993); (d) experiments in which participants made qualitative (e.g., same or different, or shorter or longer) judgments, such as duration–discrimination judgments, with only discrimination threshold data reported[2] (e.g., Arenberg, 1968; Goldstone, Lhamon, & Boardman, 1957; Rammsayer et al., 1993; Smythe & Goldstone, 1957); (e) experiments in which researchers reported only data on duration judgment error, percentage of correct judgments, or percentage underestimation or overestimation (e.g., Arenberg, 1968; Bell, 1972; Lejeune & Pouthas, 1991; Pumpian-Mindlin, 1935); and (f) experiments that might not have been excluded except that researchers did not report sufficient statistics (e.g., mean

[1] We included any relevant study listed in *PsycINFO* or *Medline* as of December 1997.

[2] Without assuming a mathematical model, this kind of judgment cannot be compared with quantitative duration judgments of the kind meta-analyzed here. Including them would subject the meta-analysis to an "apples and oranges" criticism (Sharpe, 1997).

judgment, numbers of participants, or inferential statistics) to estimate an effect size or the duration judgment ratio (e.g., Dmitriyev, 1980; R. A. Hicks, Bramble, & Ulseth, 1967; Kline & Burdick, 1980; Vanneste & Pouthas, 1995). We also excluded unpublished dissertations (Bull, 1973; Kelley, 1980) and conference presentations.[3]

Coded Variables

To identify theoretically important moderator variables, we coded the following variables from each experiment and each within-experiment condition: (a) publication year; (b) participants' sex (female, male, both male and female, or unknown); (c) participants' age (young adult, such as most samples involving college students [18.0–29.9 years of age], middle-age adult [30.0–59.9 years of age], or old adult [at least 60 years of age]); (d) predominant duration length (very short [4.9 s or shorter], short [5.0–14.9 s], moderate [15.0–59.9 s], or long [60.0 s or longer]); (e) duration judgment method (verbal estimation, production, repeated production, or reproduction); and (f) total number of duration judgments made by each participant during the experiment. Two of us coded study attributes independently, resolving any disagreements by discussion.

We also coded other theoretically relevant variables, but, for these, only one class of the variable was adequately represented; the others contained fewer than three effect size estimates. No conclusions may be drawn for such variables. Future research is needed to reveal whether any of these variables moderate age effects on duration judgments. All (or nearly all) experiments (a) used a prospective duration judgment paradigm; (b) did not state whether participants' watches were removed; (c) did not manipulate participants' body temperature; (d) did not use any arousal manipulation; (e) presented either no stimuli or one simple, continuous stimulus; (f) did not segment the duration with salient markers or high-priority events; (g) had few environmental or background changes; (h) required only passive or covert and easy or shallow processing of any presented stimuli; (i) did not involve chronometric counting; (j) used no delay, except possibly for brief instructions, preceding the duration judgment; (k) did not require memory for presented information; (l) had no changes in type or level of processing; and (m) had no concurrent task.

Effect Size Analyses

Two of us independently estimated effect sizes, resolving any disagreements by discussion. Each effect size was calculated as g, the difference between the mean duration judgment given by participants of two age classes divided by the pooled standard deviation (Hedges & Olkin, 1985), using the computer software DSTAT (Johnson, 1989, 1993). Each g was then converted to d by correcting it for bias, weighting by the reciprocal of its variance, *TW* (Hedges, 1981; Hedges & Olkin, 1985). The ds were combined by separately calculating unweighted and weighted means.[4]

If a researcher manipulated a potential moderator variable (e.g., used different duration judgment methods) and provided adequate information to calculate separate effect size estimates for each level of the variable, we did so for that moderator analysis. (To provide a single estimate of g for each experiment, we averaged all such separately calculated effect sizes.) Thus, each moderator analysis contained mainly study effect sizes as well as a few within-study effect sizes. Using more than one effect size estimate from the same experiment violates the assumption that the effect sizes are independent. However, this violation apparently does not substantially affect statistical precision (Tracz, 1985; Tracz, Elmore, & Pohlmann, 1992). If we had not calculated separate effect size estimates for each level of a manipulated variable, we could not have properly conducted the moderator analyses because we would have excluded (or coded into a mixed category) some of the most relevant information.

The homogeneity of each set of ds was tested with the Q statistic to determine whether the conditions shared a common effect size. If there was significant heterogeneity of effect sizes, we attempted to account for it with coded or manipulated study attributes. Two coded variables, publication year and the total number of duration judgments, were continuous. Those variables were fit with a weighted least-squares regression model (Hedges, 1982b; Hedges & Olkin, 1985) using SPSS and DSTAT (Johnson, 1989, 1993). All other coded attributes were categorical. For these, we used categorical models (Hedges, 1982a; Hedges & Olkin, 1985), as implemented by DSTAT. (We combined two similar classes of a variable if there were fewer than three effect size estimates in a given class.) These techniques yield a between-classes effect, which reveals whether that variable significantly moderates the age effect. We also calculated correlations among coded variables to determine the extent to which they were independent.

Primary-Level Statistics

For each condition analyzed, we calculated the ratio of subjective to objective duration—hereinafter called the *duration judgment ratio*—separately for each age class. This is a standard measure calculated and reported in many duration judgment studies (Hornstein & Rotter, 1969). It enables a comparison of duration judgments across conditions and experiments that used different durations. It reverses the commonly found negative correlation between the production method and the other methods (primarily verbal estimation) because the participant's production is the actual (objective) duration corresponding to the verbally requested (subjective) duration. Thus, this ratio assesses the moderating influence of duration judgment method without an artifactual influence of the typical negative correlation. We also calculated the mean ratio of older-to-younger mean duration judgment ratios, hereinafter called the *age ratio*. Accumulating these primary-level statistics across conditions and experiments clarifies the meta-analytic statistics (Block & Pierce, 1998).[5] Two-tailed t tests were performed on these unweighted primary-level statistics. Our descriptions of results take into account whether a particular comparison was significant ($p < .05$).

We also analyzed separately the experiments that provided sufficient information, such as standard deviations, to calculate the relative *interindividual* variability of duration judgments made by participants of different ages. One cannot simply compare standard deviations because they typically increase with increasing mean judgment when a ratio scale of measurement is involved. We instead used the common psychometric measure, the coefficient of variation, which is the standard deviation divided by the mean judgment (see, e.g., Morse, 1993; Wearden et al., 1997). This makes the reasonable assumption that duration timing involves a Poisson process. The program COEFVAR (Gilpin, 1993) was used to calculate a chi-square value for the difference between coefficients of variation with the Bennett–Shafer–Sullivan likelihood ratio test (Shafer & Sullivan, 1986). DSTAT was then used to convert each

[3] Meta-analysts do not agree on whether one should include unpublished data (Sharpe, 1997). When we included Bull's (1973) data, our findings and conclusions were not altered in any substantial way (see Tables 1 and 3). Kelley's (1980) data, however, were excluded for methodological reasons.

[4] See Block and Zakay (1997) for a more complete description of the procedures used.

[5] We also calculated weighted mean ratios, weighting each duration judgment ratio (and the age ratio) by the sample size involved. This is similar to the weighting (by *TW*) that is involved in using ds as effect size estimates in the meta-analyses. Although doing so often increased the magnitude of the age-related differences reported here, it did not alter any conclusions. We report here the unweighted mean ratios and results of t tests based on them.

chi-square to an effect size. We also accumulated and tested primary-level statistics on coefficients of variation.

As noted earlier, (see p. 587), we also evaluated studies that reported data concerning the slope, or exponent (β), of the psychophysical or regression function relating subjective and objective duration across different duration lengths.

Results and Discussion

A total of 16 experiments, published in 16 separate journal articles, met all criteria for inclusion in our review. A total of 15 articles were written in English and 1 in Spanish. The median publication year was 1977.5. The mean age of participants was about 25.1 for young adults, 43.2 for middle-age adults, and 70.8 for old adults.

Duration Judgment Magnitude

Effect Size and Primary Statistics

Of the 16 experiments, 14 contributed an effect size for magnitude of duration judgments made by younger adults compared with older adults (see Table 1). All used a between-subjects design; none was a longitudinal study. A total of 12 effect sizes were calculated from means and standard deviations, standard errors, or similar measures of variability; 1 from means and a pooled standard deviation estimated from a related F value; and 1 from a reported F value. We defined an effect as being positive if the mean duration judgment ratio was greater for older participants and as negative if it was greater for younger participants. The resulting weighted mean effect size, $d_+ = 0.40$, 95% confidence interval (CI) = 0.28 to 0.52, indicated that the duration judgment ratio was greater for older than younger participants ($p < .0001$). Effect sizes were not homogenous, $Q(13) = 31.5$, $p = .003$, so we used coded study attributes to account for variability in them.

The d_+ of 0.40 is considered small to moderate in magnitude. The mean duration judgment ratio was greater for older than for younger participants, $t(13) = 4.25$, $p < .001$, and the mean older-to-younger (age) ratio of 1.21 was greater than 1.00, $t(13) = 24.5$, $p < .001$. Even though the effect size was only small to moderate, the age ratio revealed a relatively large difference: The mean duration judgment ratio was 21% greater for older than for younger participants, which is in the opposite direction from what is usually predicted.

Moderator Variables

Table 2 shows the results of model testing involving the only significant categorical moderator variable: duration judgment method.

Duration judgment method. Because only two experiments used the method of repeated production, we combined them with the seven that used the method of production. Duration

Table 1
Duration Judgment Ratios and Effect Sizes

Study	Older Ratio	Older *n*	Younger Ratio	Younger *n*	Older-to-younger ratio	Total *N*	Effect size (*d*)
Feifel (1957)[a]	1.43	40	1.11	39	1.29	79	1.03*
Goldstone et al. (1958)[a,b]	1.24	20	0.97	20	1.29	40	0.87
Surwillo (1964)[c,d]	1.24	80	1.01	80	1.23	160	0.47
McGrath & O'Hanlon (1968)[e,f]	1.20*	24	0.75*	24	1.60*	48	1.37
McNanamy (1968)[a,g]	1.03	36	1.08	72	0.96	108	−0.17
LeBlanc (1969)[a,c,e]	1.64	79	1.32	33	1.25	112	0.40*
Neuringer & Levenson (1972)[c,h]	1.77	15	1.20	15	1.44	30	0.54
Bull (1973)[a,c,e,i]	1.39	60	1.15	30	1.21	90	0.45
Newman (1976; see 1982)[c]	1.29	45*	0.93	45*	1.39	90	0.46
Kline et al. (1980)[a]	1.00	12	0.86	12	1.16	24	0.23*
Landaeta et al. (1981)[a]	1.34*	20	1.15*	20	1.17*	40	0.31
Licht et al. (1985)[c]	1.33	30	1.24	15	1.08	45	0.29*
Beck (1988)[e]	1.33	10	1.42	85	0.94	95	−0.15
Polyukhov (1989)[a,c,e]	1.00*	164*	0.90*	92*	1.11*	256	0.23
Eisler & Eisler (1994)[e]	0.92*	24	0.88*	24	1.05*	48	0.60
Overall mean (unweighted)[j]	1.27*	14	1.06*	14	1.21*	14	0.46*
Overall mean (weighted)[k]	1.23*	599*	0.99*	576*	1.24*	1,175	0.40*

Note. Position effect size (*d*) indicates that the mean duration judgment ratio (subjective-to-objective duration) was greater for older adults; negative effect size (*d*) indicates that it was greater for younger adults. Older = middle-age or old adults. Younger = young or middle-age adults. * An approximate datum (e.g., one estimated from a figure).
[a] Study compared old adults and young adults. [b] We excluded Smythe and Goldstone's (1957) "passive estimation" data. [c] Study compared old adults and middle-age adults. [d] We pooled data from two subgroups. [e] Study compared middle-age adults and young adults. [f] We used a median split for age (20–30 and 30–50 years old, respectively). [g] We combined pretest and trials. [h] We included only geriatric and normal groups. [i] We show these unpublished data for the sake of completeness; we did not include them in any of the analyses. [j] Each mean weights each experiment equally. [k] Each mean weights by *n* contributing to each datum (and by *TW* for effect size).

Table 2
Test of Categorical Model for Duration Judgment Comparisons

Variable and class	Between-classes effect (Q_B)	k	Mean effect size (d_{i+})	95% CI for d_{i+} Lower	Upper	Homogeneity within class (Q_{wi})[a]
Duration judgment method	15.26**					
Verbal estimation		4	0.27	0.05	0.48	3.58
Production or repeated production		9	0.60	0.44	0.76	13.56
Reproduction		3	−0.02	−0.31	0.27	6.20

Note. Positive mean effect size (d_{i+}) indicates that the mean duration judgment ratio (subjective-to-objective duration) was greater for older adults; negative mean effect size (d_{i-}) indicates that it was greater for younger adults.
[a] None of the values was sufficiently large to reject the hypothesis of homogeneity of effect sizes.
** $p < .001$.

judgment method moderated effect sizes. The age effect was greater for the method of production or repeated production than for the methods of verbal estimation ($p < .05$) and reproduction ($p < .001$). Only effect sizes for production and verbal estimation were significantly greater than zero. No method category showed significant heterogeneity of variance, so duration judgment method adequately accounted for the age effect. Older participants gave a greater duration judgment ratio in conditions using the methods of verbal estimation (1.42) and production or repeated production (1.36) than in conditions using the method of reproduction (0.95). However, younger participants gave a greater duration judgment ratio using the method of verbal estimation (1.19) than the method of production or repeated production (1.05) and the method of reproduction (0.91). The age ratio was greater for production or repeated production (1.28) and verbal estimation (1.19) than for reproduction (0.99); the former two did not differ.

Figure 1 clarifies the significant moderating effect: Compared with younger adults, older adults gave larger verbal estimates and made shorter productions (both of which entail a greater duration judgment ratio), but they made comparable reproductions. The findings concerning verbal estimates and productions are the opposite of what some theories predict, such as the notion that a pacemaker rate slows with aging. The conclusion that reproductions do not show age effects should be regarded skeptically because, although Eisler and Eisler (1994) reported small effects, they were significant.

Publication year. The moderating influence of publication year was significant ($Q_R = 5.60$, $p = .01$); however, the linear regression model did not provide a good fit ($Q_E = 25.47$, $p = .01$). The correlation between publication year and effect size was marginally significant, $r(12) = -.50$, $p = .07$, and the slope of the regression function was −.44. Thus, earlier studies showed a greater effect size. This may be explained by the fact that experiments using the method of production, which yielded the largest age effects, tended to be published earlier (median date = 1969) than those using the methods of verbal estimation and reproduction (median dates = 1984.5 and 1981, respectively).

Other variables. The median number of duration judgments that each participant made in an experiment was four. The linear moderating influence of number of duration judgments was not significant ($Q_R = 1.62$, $p = .20$), and the linear regression model did not provide a good fit ($Q_E = 29.84$, $p < .003$). Several other variables were sufficiently represented across studies or frequently manipulated in experiments. However, there was no significant moderating influence of older participants' age, younger participants' age, or participants' sex. (See Tables 1, 3, and 4 for information about the age classes of participants in each experiment.)

We describe the relevant findings concerning duration length here because of their theoretical importance (also see the follow-

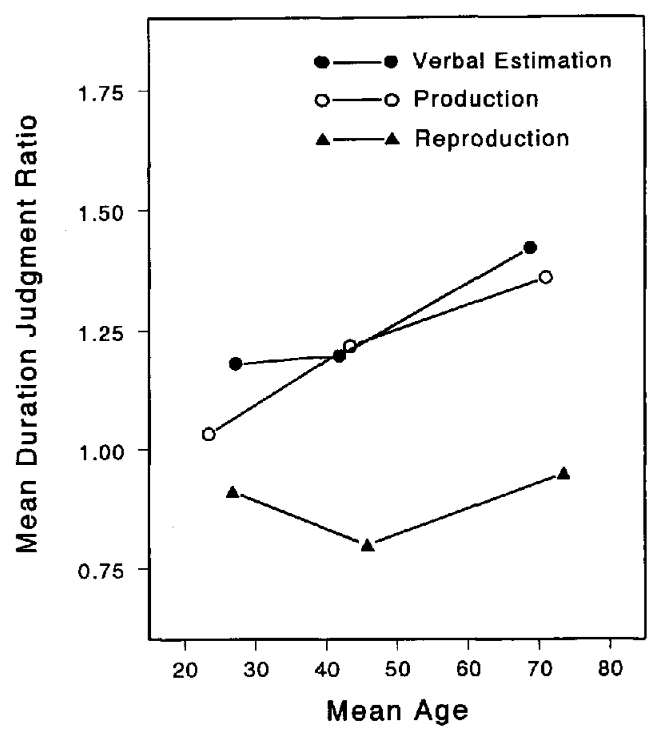

Figure 1. Mean duration judgment ratio as a function of age class shown separately for each duration judgment method.

Table 3
Coefficients of Variation (CV) and Effect Sizes

Study	Older CV	Older *n*	Younger CV	Younger *n*	Older-to-younger CV	Total *N*	Effect size (*d*)
Goldstone et al. (1958)[a,b]	0.33	20	0.24	20	1.38	40	0.39
Surwillo (1964)[c,d]	0.42	80	0.32	80	1.31	160	0.35
LeBlanc (1969)[a,c,e]	0.50	79	0.38	33	1.32	112	0.32*
Neuringer & Levenson (1972)[c,f]	0.52	15	0.47	15	1.11	30	0.11
Bull (1973)[a,c,e,g]	0.44	60	0.28	30	1.55	90	0.53
Licht et al. (1985)[c]	0.54	30	0.32	15	1.69	45	0.57*
Beck (1988)[e]	0.53	10	0.37	85	1.43	95	0.50
Polyukhov (1989)[a,c,e]	0.43*	164*	0.29*	92*	1.48*	256	0.35
Overall mean (unweighted)[h]	0.47*	7	0.34*	7	1.39*	7	0.37*
Overall mean (weighted)[i]	0.45*	398*	0.33*	340*	1.40*	738	0.36*

Note. Positive effect size (*d*) indicates that the mean coefficient of variation was larger for older adults. Older = middle-age or old adults. Younger = young or middle-age adults. * An approximate datum (e.g., one estimated from a figure).
[a] Study compared old adults and young adults. [b] We excluded Smythe and Goldstone's (1957) "passive estimation" data. [c] Study compared old adults and middle-age adults. [d] We pooled data from two subgroups. [e] Study compared middle-age adults and young adults. [f] We included only geriatric and normal groups. [g] We show these unpublished data for the sake of completeness; we did not include them in any of the analyses. [h] Each mean weights each experiment equally. [i] Each mean weights by *n* contributing to each datum (or by *TW* for effect size).

ing section on psychophysical slope). Across all experiments, the target duration ranged from 1.3 s to 480.0 s.[6] Duration length was not a significant categorical moderator variable, $Q_B(2) = 2.48$, $p = .29$, and all weighted mean effect sizes were significantly greater than zero (d_+s = 0.34, 0.34, and 0.53 for very short and short durations, moderate durations, and long durations, respectively).[7]

Coefficient of Variation

Seven published reports contained enough information to calculate coefficients of variation for older and younger adults (see Table 3). The sign of each effect size was positive if the mean coefficient of variation was greater for older participants and was negative if it was greater for younger participants. The resulting weighted mean effect size, $d_+ = 0.36$, 95% CI = 0.20 to 0.52, indicated a greater coefficient of variation for older than for younger participants ($p < .0001$). The homogeneity of effect sizes was indicated, $Q(6) = 1.13$, $p = .98$, and no variable significantly moderated them.

The weighted mean effect size, $d_+ = 0.36$, although significant, is considered small to moderate in magnitude. The mean coefficient of variation was greater for older than younger participants, $t(6) = 6.08$, $p < .001$, and the mean age ratio of 1.39 was greater than 1.00, $t(6) = 20.7$, $p < .001$. Even though the effect size was small to moderate, the age ratio revealed a relatively large difference: The mean coefficient of variation was 39% greater for older than younger participants, indicating that older adults showed substantially more interindividual variation than did younger adults (see Figure 2).

Psychophysical Slope

Four published experiments provided data on the slope of the psychophysical or linear regression function relating judged duration and target duration for older and younger adults (see Table 4). In two experiments, Salthouse, Wright, and Ellis (1979) obtained analog magnitude judgments of very short (40–1,000 ms) durations of light or dark. Nichelli, Venneri, Molinari, Tavani, and Grafman (1993) obtained verbal estimates of a 5- to 40-s task (exposing digits at a 1-s rate). Eisler and Eisler (1994), who performed the most extensive study, had participants reproduce 1.3- to 20.0-s tones. The sign of each effect size was positive if the slope was greater for older participants and was negative if it was greater for younger participants. The resulting weighted mean effect size, $d_+ = 0.04$, 95% CI = −0.29 to 0.37, indicated no significant difference in slopes for older and younger participants ($p = .82$). The homogeneity of effect sizes was indicated, $Q(3) = 0.37$, $p = .95$. Thus, there was no significant age-related difference in the slope of the function relating duration judgments to actual duration. These data are inconsistent with the notion that there is an age-related difference in pacemaker rate that is not recalibrated (compensated) by a gradual learning of correspondences between pacemaker pulses and numerical labels for durations. In other words, if there are age-related differences in pacemaker rate, these differences are also at least adequately compensated for by changes in reference memory information.

Summary and Theoretical Discussion

The duration judgment meta-analyses revealed several important findings regarding the influence of age on mean duration

[6] Additionally, Salthouse, Wright, and Ellis (1979) used very short (40–1,000 ms) durations; see the section on psychophysical slope.

[7] Duration length was also tested as a continuous moderator variable using the mean target duration when necessary. The linear moderating influence of duration length was not significant ($Q_R = 0.12$, $p = .73$).

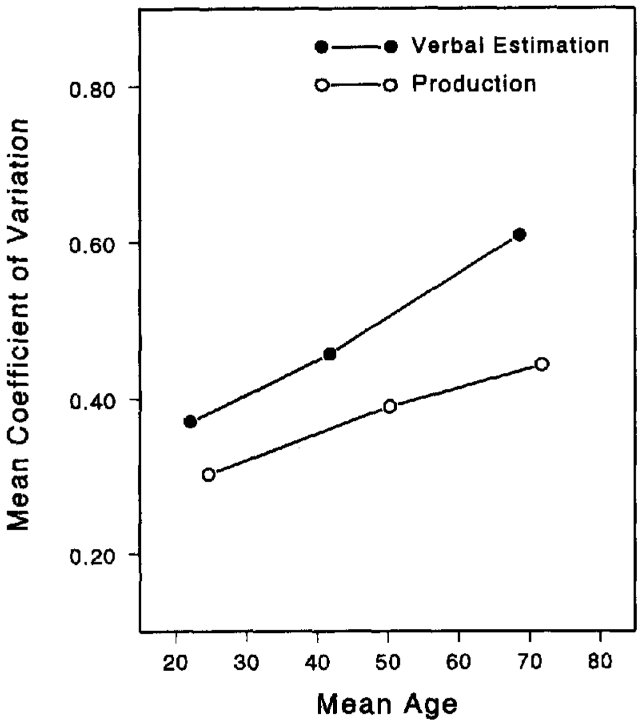

Figure 2. Mean coefficient of variation as a function of age class shown separately for each duration judgment method. No experimental report contained enough data to calculate coefficients of variation for the reproduction method.

judgment. The overall weighted mean effect size suggested that older participants' duration judgments differed significantly from those of younger participants: The ratio of subjective to objective duration was relatively larger for older adults. When we tested categorical models investigating potential moderator variables and aggregated primary-level statistics (duration judgment ratios), the duration judgment method was found to be the only important moderator variable. Older adults differed from younger adults in that they gave larger verbal estimates and made shorter productions of duration, but they made fairly comparable reproductions. This was the case regardless of the duration length used. Considerable evidence reveals that judgments of durations less than several seconds entail different processes than judgments of longer durations (for reviews, see Block, 1979, 1990; Fraisse, 1984; Pöppel, 1985/1988). However, our age-related differences in duration judgments did not depend on duration length.

The findings concerning verbal estimates and productions were the opposite of what some theories predict, such as the notion that a pacemaker rate slows with aging. For these methods, older participants' judgment ratios (relating subjective duration to target duration) were greater, not less, than those of younger participants. As McGrath and O'Hanlon (1968) aptly noted, "a given interval of time seems longer as [a person] grows older. This is in direct opposition to the traditional view" (p. 1087). Licht, Morganti, Nehrke, and Heiman (1985) commented that

> conflicting interpretations questioning whether brief intervals of real time are perceived as passing more or less rapidly with increasing age have been reported. Reasons for these inconsistent results lie in semantic confusions, in variations in methodology, and in the effects of other mediating [moderating] variables. (p. 211)

Our analysis suggests one important moderating variable: Age-related effects may be found using only absolute methods, verbal estimation or production, in which a person must translate from subjective experience to a conventional verbal label (i.e., numerical quantity), or vice versa. There is not yet enough evidence that older adults differ from younger adults on the most commonly used duration judgment method that requires a comparison of durations: reproduction.

The mean coefficient of variation was greater for older than for younger adults. As we mentioned earlier, there are several possible explanations for this finding, such as greater interindividual variation in the kinds of processes or greater intraindivid-

Table 4
Psychophysical or Regression Slopes and Effect Sizes

Study	Older Slope	Older *n*	Younger Slope	Younger *n*	Older-to-younger slope	Total *N*	Effect size (*d*)
Salthouse et al. (1979, Experiment 1)[a]	1.31	18	1.33	15	0.98	33	−0.06
Salthouse et al. (1979, Experiment 2)[a]	1.23	22	1.21	23	0.98	45	0.06
Nichelli et al. (1993)[b]	0.90*	15	0.83*	5	1.08*	20	0.29*
Eisler & Eisler (1994)[c]	0.87	24	0.87	24	1.00	48	0.01
Overall mean (unweighted)[d]	1.08*	4	1.06*	4	1.02*	4	0.08*
Overall mean (weighted)[e]	1.08*	79	1.09*	67	0.99*	146	0.04*

Note. Positive effect size (*d*) indicates that the psychophysical or regression slope was larger for older adults; negative effect size (*d*) indicates that it was larger for younger adults. Older = middle-age or old adults. Younger = young or middle-age adults.
* An approximate datum (one estimated from a figure).
[a] Study compared old adults and young adults. [b] Study compared old adults and middle-age adults. [c] Study compared middle-age adults and young adults. [d] Each mean weights each experiment equally. [e] Each mean weights by *n* contributing to each datum (or by *TW* for effect size).

ual variation in common component processes (see also Morse, 1993).

Only a few experimental reports contained data on the slope of the psychophysical or regression function relating judged duration to target duration. There were no significant age-related differences in the slope, a finding that is not compatible with the hypothesis that there is an age-related difference in pacemaker rate (unless such a difference is also accompanied by a recalibration of reference memory). Consider several potential explanations for our age-related differences in duration judgments, which we introduced earlier.

Pacemaker Rate

One way to explain the difference between younger adults and older adults is to assume that duration judgments reflect only the rate of a pacemaker or other similar component of an internal clock. Theorists usually assume that a pacemaker that is not rate-compensated should operate more slowly in older adults. A slower pacemaker rate would shorten subjective duration. Our findings are in the opposite direction. Perhaps the pacemaker runs faster in older adults, or perhaps older adults overcompensate for a slower pacemaker. These explanations are clearly post hoc, fairly implausible, and difficult to test. Note that the finding that no significant age-related effects occurred in studies using the reproduction method does not effectively challenge the pacemaker-rate hypothesis. In this method, any individual differences in pacemaker rate present during the target duration are also present during the reproduction, effectively reducing the effect of such individual differences on the duration judgment ratio.

Metabolic Rate or Body Temperature

Previous research suggests that experienced duration lengthens as body temperature increases (Hancock, 1993), and it is worthwhile to consider whether our findings can be explained in terms of this effect or allied influences such as basal metabolic rate. Temperature or metabolism may affect a central time-generating mechanism, which may directly affect duration juugments (Hoagland, 1933; Hoagland & Perkins, 1935) or form the basis of a more complex hybrid model in which it is only one component (Treisman, 1963; Treisman, Faulkner, Naish, & Brogan, 1990; Wearden & Penton-Voak, 1995). To account for age-related differences in duration judgments, there must be similar age-related changes in temperature or metabolism. Such changes are in the form of a monotonically decreasing function (Altman & Dittmer, 1968; Kadlub, 1996). However, a temperature or metabolic hypothesis faces the same difficulties as the pacemaker-rate hypothesis: Duration judgments obtained using the methods of verbal estimation and production are the opposite of what is predicted. If temperature and metabolism play a role in duration judgments, they are not the only important influences. At the least, a hybrid model is needed.

Memory Processes

Another possibility is that there are age-related differences in memory processes, such as in the rate of forgetting of information (cf. Inglis, 1965). In this kind of explanation, the observed differences between participants of different ages reflect a more rapid loss of information concerning events, especially those nearer to the start of a time period. If older adults forget those events at a greater rate than do young adults, they may infer from the decreased memory strength of early events that the duration is relatively longer. Thus, verbal estimates would increase and productions would shorten. One problem with this potential explanation is that the reproduction method should reveal such memory effects, in that a person must remember the target duration at the time he or she is making a reproduction. Indeed, the reproduction method usually reveals large effects in people displaying severe memory disorders (e.g., Richards, 1973). Kelley (1980) and Vanneste and Pouthas (1995, Experiment 2) obtained evidence supporting the notion that memory may play a role in producing age-related differences in the retrospective paradigm: Older adults made shorter reproductions than did younger adults. However, as noted earlier, we were not able to include these data in our meta-analyses. Data included in the present meta-analyses, all of which came from the prospective paradigm, are amenable only to post hoc explanations in terms of age-related memory differences.

Attentional Resources

Some evidence suggests that older adults may have more limited attentional resources than do younger adults. Age-related differences in attentional resources are revealed most clearly in divided-attention tasks: Older adults may ordinarily have fewer attentional resources with which to divide attention. Prospective timing requires that a person divide attention between nontemporal (stimulus) information processing and temporal information processing. An attentional-gate model (Zakay & Block, 1997), which includes a pacemaker but emphasizes the role of attention, can explain the present findings as well as the moderating influence of duration judgment method. This model predicts that experienced duration (i.e., duration experience in a prospective paradigm) lengthens as a function of the amount of attentional resources that a person allocates to processing temporal information, as opposed to processing nontemporal (stimulus) information. In this account, verbal estimation and production of duration rely on translations between duration experience and conventional temporal units. These translations are learned in everyday situations. With only one exception, the experiments reviewed here used either no nontemporal information processing task or an easy concurrent task during the target duration. Compared with everyday situations in which older adults must process nontemporal information at a considerable rate, in the present experiments the older adults would have had an unusually large amount of residual resources with which to attend to time. This would increase their verbal estimates and shorten their productions, just as our data show.

This explanation predicts that the greater subjective-to-objective duration ratio in older adults should be eliminated or reduced if the time period contains a difficult information-processing task. In fact, McNanamy (1968) found no significant age-related difference in the mean reproduction of 30-s durations spent viewing a series of complex polygons. Polyukhov (1989) reported the typical age-related increase when participants performed no task ("empty" interval), but no significant age-related effect when participants performed a relatively difficult verbal task ("creating sentences using proposed words"). Craik and Hay (in press) also used a relatively difficult nontemporal information-processing task, and they found the opposite of what is revealed in the present meta-analysis: Older adults gave smaller verbal estimates and made longer productions than did younger adults. Additional studies like these, using tasks varying in difficulty, are needed to help to clarify the role of attentional demands in duration judgments made by younger and older participants.

Conclusions

The finding that older adults gave a greater duration judgment ratio (larger verbal estimates and shorter productions) than did younger participants is surprising because it is in the opposite direction from what is predicted based on the notion that a biological pacemaker operates more slowly with aging. Existing experimental methodology might have been insufficient to reveal such a biological effect. In any event, an explanation must be sought elsewhere for the oft-repeated idea that time passes more quickly when one ages. James (1890) may have been correct to suggest that different age-related temporal experiences occur over shorter and longer time periods.

Perhaps the best explanation for the differences we found here arises from the observation that nearly all experiments used empty durations. The situation in which participants found themselves differed greatly from many everyday situations. If aging is accompanied by a decrease in processing resources, as other evidence suggests, in many everyday situations older adults may ordinarily be sufficiently occupied with information processing that they cannot attend much to time. Because the present experiments tended to lack such attentional demands, the older adults may have found it unusually easy to attend to time during the experimental duration. This would then lengthen their experienced duration because more subjective temporal units would have accrued than is usually the case for a duration having a certain number of objective (verbally labeled) units.

Time is central to all behavior; atemporal behavior is an oxymoronic notion. Our findings offer intriguing glimpses into potential explanations of cognitive aging. In addition, they begin to address the largely unresolved problem of individual differences in temporal judgment. The findings reveal that absolute methods of duration judgment (e.g., verbal estimation and production) are distinct from relative methods (e.g., reproduction). Absolute duration judgment methods may clearly reveal individual differences, whereas relative methods are sometimes not sensitive enough to do so.

The literature on aging and duration judgment is clearly limited. No published study contained enough data for us to evaluate younger and older adults' retrospective duration judgments; future studies using a retrospective paradigm may help clarify the age-related differences found here in the prospective paradigm. Additional studies (e.g., Craik & Hay, in press) that vary information-processing difficulty, especially at the higher ranges of difficulty, are also critically needed. The present review provides several excellent reasons for researchers to continue to explore age-related differences in duration judgments.

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