The Study of Time

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Chapter Thirteen – Relationships between Subjective Time and Information Processed (Reduction of Uncertainty)

SUMMARY

We discuss how information processing may change over a person's lifespan and how changes in information processing may influence a person's experience of time. Two assumptions are considered: (a) Subjective time is related to the overall information-processing rate, and (b) the experience of duration is related to the total amount of information processed (cumulative reduction of uncertainty). Taken together, these assumptions suggest that age-related changes in human information-processing rate may be at least partly responsible for the "quick passage of time" that is associated with aging. In addition, a person's experience of the duration of his or her life (and longevity) may be related to the cumulative amount of information processed.

To explore these issues, we review evidence on age-related changes in time estimation (duration judgment). These age-related changes may be influenced by several factors. We review age-related changes in (a) information-processing rate, as revealed by studies on reaction time; (b) body temperature; (c) divided attention; and (d) memory. Finally, we discuss an implication of these assumptions, that human experience of longevity can be increased not only by increasing chronological age but also by increasing the information-processing rate and thereby the total information processed.

The notion that subjective time is related to information processing was introduced more than a hundred years ago by some psychologists, especially Guyau (1890/1988) and James (1890). Although neither Guyau nor James used the term *information processing*, they both discussed the influences of the number of stimuli, the intensity of stimuli, differences between stimuli, and other such information-processing considerations. They both thought that subjective time is not determined so much by clock time (or proper time) as by the events people experience. More recently, Michon (1967, 1993) also adopted the view that psychological time is a product of a person's information processing activities.

In this article, we focus mainly on the how information processing may change over a person's lifespan and how changes in informa-

tion processing may influence a person's experience of time. We consider two main assumptions: (a) Subjective time is related to the overall information-processing rate, and (b) the experience of duration is related to the total amount of information processed (cumulative reduction of uncertainty). Taken together, these assumptions suggest that age-related changes in human information-processing rate may be at least partly responsible for the "quick passage of time" that is associated with aging. In addition, a person's experience of the duration of his or her life (and longevity) may be related to the cumulative amount of information processed.

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Information and Uncertainty Reduction

Since the seminal contribution of Shannon and Weaver (1949), theorists view information processing in terms of reduction of uncertainty. The relationship between information and uncertainty may be clarified by an example of weather patterns and forecasts. Weather information can be recorded for the city of Seattle by denoting a 1 for a rainy day and a 0 for a dry day. A typical record for 50 consecutive days in Seattle might look like this: 001110100100101011-00111010100101100011110100100101. In these data, the probability of a dry day and the probability of a rainy day are both exactly .50. One glance at these data suggests that there is considerable uncertainty about what the weather will be like on a particular day.

In contrast, the city of Tucson typically has dry weather, and 50 consecutive days might look like this: 0000000000000000000000001-00000000010000000000000000. In these data, the probability of a dry day is .96, and the probability of a rainy day is .04. One glance at these data suggests that there is much less uncertainty about what the weather will be like on any particular day. Moreover, Tucson's information can be compressed with the aid of an algorithm (that itself requires a few bits of information) to far less than 1 bit/day.

As a result of this compression (to "algorithmic information"), the record for Tucson contains less information than does the record for Seattle, and the uncertainty of when it will and will not rain is much less than for Seattle.[1]

In short, information may be understood in terms of uncertainty, and information processing may be understood in terms of uncertainty reduction. If a communication (e.g., a weather forecast) contains more information, the prospective uncertainty is greater, and when a person processes the communication, the person's uncertainty is more greatly reduced. Because the literature on subjective time is usually stated in terms of information than in terms of uncertainty, we will use the term *information* in this article.

Information-Processing Rate and Age

Soon after information theory was developed, psychologists who investigated human information processing discovered an interesting characteristic of it (Hick, 1952; Hyman, 1953). One of the crudest but simplest ways to measure human information processing is by observing the time it takes a person to react to a stimulus (or to a series of stimuli). In fact, reaction time is a function of information processed. The shorter the reaction time (latency of the person's response) or the more bits a person processes during a time period, the faster is the person's information-processing rate. Hick discovered that the typical information-processing rate for humans is about 5 bits/s. Hyman clarified the way in which stimulus information determined a person's reaction time. This became known as the Hick-Hyman Law, RT = $a + bH$, where RT is reaction time, a and b are constants, and H is the amount of information transmitted (in bits).

Many psychologists have commented that time seems to pass more quickly as a person ages (for reviews, see Fraisse, 1957/1963, Block, Zakay, & Hancock, 1998). Rosenberg (1979) theorized that this seemingly more rapid passing of time might be attributed, at least in part, to changes in the person's information-processing rate. In Figure 1, the mean processing rate at any age is expressed as a percentage of that noted at about age 20, the age of maximum performance (Fry & Hale, 1996; Lawrence, Meyerson, & Hale, 1998).

[1] Formally, the amount of information (H), measured in bits, is defined in terms of the probability of some event (p_e): $H = \log_2 (1/p_e)$. In the Seattle example, $\log_2 (1/p_e) = \log_2 (1/.50) = 1.00$ bit of information for a dry forecast and the same for a rainy forecast. Averaged over a large number of Seattle days, the weather report communicates 1.00 bit/day. In the Tucson example, $\log_2 (1/p_e) = \log_2 (1/.96) = 0.06$ bit of information for a dry forecast and $\log_2 (1/p_e) = \log_2 (1/.04) = 4.64$ bits for a rainy forecast. Averaged over a large number of Tucson days, the weather report communicates $(0.06 \times 0.96) + (4.64 \times 0.04) = 0.24$ bit/day. Thus, a typical Seattle forecast contains more information than does a typical Tucson forecast; in other words, a Seattle forecast reduces uncertainty more than does a Tucson forecast.

Thus, for a variety of tasks (verbal and visuospatial), the mean information-processing rate increases from birth, reaches a maximum at about age 20, and declines thereafter. At age 10, the mean information-processing rate is about 61% of what it is age 20. At age 60, the mean verbal and visuospatial information-processing rate drops to 50% of that value.

To estimate the amount of information processed in a lifetime, we define the total information processed in the 20th year as one bit-year. Then, if we know the information-processing rate (the *bit rate*) for each year (by taking the mean of the visuospatial and verbal

Information-Processing Speed Changes with Age

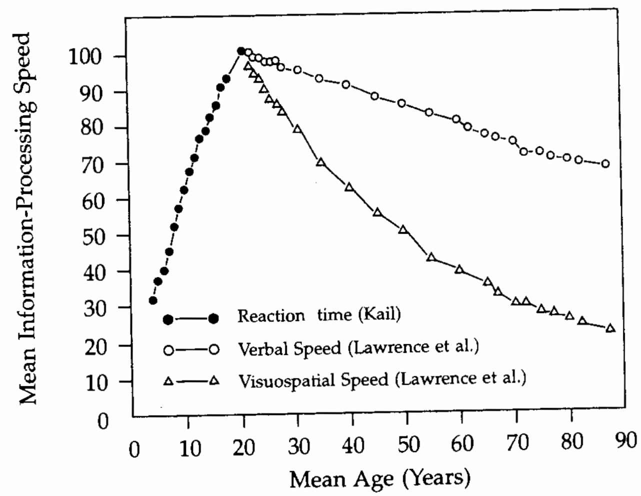

Figure 1. The mean information-processing rate (of verbal and visuospatial information-processing tasks) increases from birth and reaches a maximum at about age 20. The processing rate at any age is expressed as a percentage of that at about age 20, the age of maximum performance. Data are adapted from equations in Kail (1991) and Lawrence et al. (1998) which provide "processing time coefficients." These coefficients provide a general processing rate index. The reciprocal of the coefficients (which was used here) provide an index of the relative decline in processing rate on either side of approximately age 20 (the age of maximum performance).

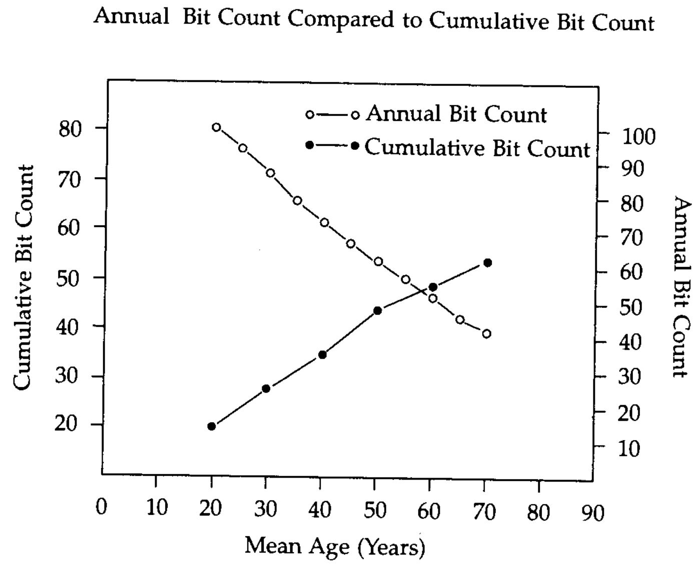

Figure 2. The total information processed in the 20th year is defined as one bit year. Based on the information-processing rate for each year (e.g., the mean of the visuospatial and verbal information-processing rates), one can calculate the yearly bit count. Although the yearly bit count decreases beginning at about age 20, the cumulative bit count (called the *bit age*) increases with age. The bit age does not equal the chronological age. In fact, the bit age of the average 60 year-old is approximately 50 bit-years.

information-processing rates, for example), we can calculate the yearly bit count. Although the yearly bit count declines each year after age 20, the cumulative bit count (called the *bit age*) increases with aging (see Figure 2).

Because the yearly bit count declines after age 20, the bit age does not equal the chronological age. In fact, the bit age of the average 60 year-old is about 50 bit-years. In essence, the cerebral mileage of a 60–year-old is less than it would have been had his or her information-processing rate not declined over time. Unfortunately, we cannot make these calculations for individuals.

Information-Processing Rate, Temperature, and Subjective Time

Psychological studies have linked a person's subjective time to his or her information-processing rate, and both have been linked to body (i.e., brain) temperature. Hoagland (1966) reported that he went to the drugstore to get some medicine for his wife, who had a fever

of 40°C. He was gone for 20 minutes, yet on his arrival his wife insisted that he was gone for 30 minutes. Since then, more controlled experimentation has revealed that a person's experience of duration tends to lengthen as body temperature increases (Hancock, 1993). Siffre (1963), a young geologist, lived alone in a cave on a floor of melting ice in near-freezing conditions. He suffered from near-hypothermia, a condition of semi-hibernation. Upon emerging from the cave after a period of two months, he estimated that he had been in the cave for only about four weeks. In addition, deep-sea divers whose body temperatures drop precipitously return to the surface claiming that they had been underwater for much less time than the clock actually stated (Baddeley, 1966).

Duration judgments may turn out to correlate well with information-processing rates in these studies. However, body temperature does not do so. Decreased body temperature leads to a decrease in a person's information-processing rate and reaction time (Rammsayer, Bahner, & Netter, 1995). However, increased body temperature has not been consistently shown to increase a person's information-processing rate or reaction time (Akerstedt, Patkai, & Dahlgren, 1977; Travlos & Marisi, 1996). Changes in information-processing rates with aging are probably more a result of brain deterioration than a brain temperature decrease (Cerella, 1990). Furthermore, body temperature (and basal metabolism) does not peak at age 20; it decreases monotonically across the lifespan (Altman & Dittmer, 1968). Thus, changes in subjective time over the lifespan are not likely to be solely a result of body (i.e., brain) temperature changes.

However, subjective time estimates can be made prospectively or retrospectively, and these two kinds of estimates may differ. When tested prospectively (i.e., when subjects know in advance that they will make time estimates), people with decreased body temperatures do not show decreased time estimates for target durations of one hour (Aschoff, 1998). When tested retrospectively (i.e., when subjects do not know in advance that they will make duration judgments), duration judgments decrease when body temperature falls by as little as 0.5°C. (e.g., Campbell, Murphy, & Boothroyd, 2001).

Information-Processing Rate and Attention

Another age-related factor that influences duration judgments on the order of seconds to minutes is attention. Attentional allocation is arguably the most important factor influencing prospective duration judgments. At any moment, a person may be attending to external (stimulus, or nontemporal) information processing or to internal temporal information (attention to time). If a person is required to process little or no information during a time period, prospective duration experience lengthens, presumably because the person is allocating considerable attentional resources to temporal information. If a person is required to perform a difficult information-processing task, prospective duration experience shortens, presumably because the person is not able to allocate many attentional resources to temporal information (Block & Zakay, 2001).

Age-related changes in attentional resources have been well documented. As a person ages from early adulthood to late adulthood, the total attentional resources decrease, and the person has difficulty performing divided-attention tasks. Prospective timing is a divided attention task in that a person must process both nontemporal (stimulus) information and temporal information. If older adults have fewer attentional resources, their prospective duration experience may shorten, especially in situations characterized by more difficult information-processing demands (Vanneste & Pouthas, 1999; Perbal, Droit-Volet, Isingrini, & Pouthas, 2002).

Prospective and Retrospective Time Estimation (Time Perception)

Until recently, researchers investigating age-related changes in subjective time (time perception) have used short durations (on the order of seconds and minutes) devoid of any information-processing (attention-demanding) task. In two meta-analyses, Block, Zakay, and Hancock (1998, 1999) found that prospective time estimates change from about the ages of 10–72. In Figure 3, we have combined their findings, with the duration judgment ratio (the ratio of the subjective to objective time) plotted as a function of chronological age. The results varied depending on the method of testing. For example, using the verbal estimation method (in which a person estimates a duration in numerical units such as minutes and seconds), the duration judgment ratio decreases from age 10 to about age 20–25, but increases again to about age 70. These data reveal a nonmonotonic (U-shaped) function over the lifespan, which appears to be the opposite of what Rosenberg (1979) predicted. However, these meta-analyses were necessarily based on the extant primary literature. This literature is an inadequate reflection of the kinds of everyday situations faced by children, young adults, and older adults. Specifically, as these findings apply to the effects of aging on duration experience, all of the reviewed experiments used a duration during which no nontemporal (stimulus) information processing was required – that is, the duration was "empty."

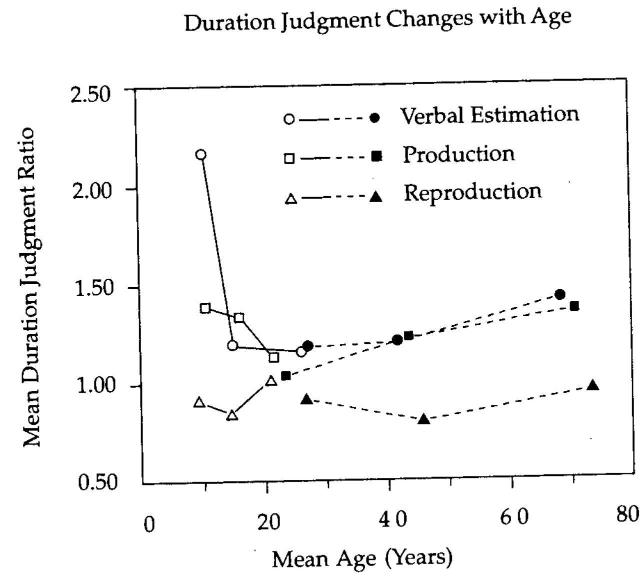

Figure 3. In two meta-analyses, Block et al. (1998, 1999) noted the change in prospective time estimation from age 10–72. The duration judgment ratio (the ratio of the subjective to objective time) is plotted as a function of age. The results varied depending on the method of testing.

More recently, it has become clear that compared to young adults, older adults give a smaller (not a larger) ratio of subjective-to-objective duration if they are estimating a time period during which an information-processing task was required, a "filled" duration (Craik & Hay, 1999; Gambara, Botella, & Gempp, 2002; Perbal et al., 2002). It is only if a duration is "empty" that the experience of duration in passing is lengthened in older adults relative to young adults. Under more everyday conditions, in which durations are "filled," older adults experience duration as being relatively short.

Retrospective time-estimation studies show a different pattern of results. As we noted earlier, many psychologists have claimed that subjective time seems to accelerate as a person ages. This impression is probably based more on long-term memory and on retrospective duration experience than on short-term memory and prospective duration experience. Specific studies to measure any age-related acceleration of the passing of time (in terms of days, months, and years) did not begin until relatively recently. Lemlich (1975) asked people of various ages to indicate how much slower or faster the years seems to go by at the present time than when they were approximately one-half their present age. Almost all adults indicated that time seems to pass faster now than it did during a former period in their lives. Furthermore, middle-age adults report that time seems to pass more quickly than young adults do. These kinds of judgments are probably difficult to make, however, and it is likely that the results reflect stereotyped beliefs of the respondents and demand characteristics of the survey as much as they reflect the actual impression of the rate of passage of time.

Only two research groups have reported experiments on retrospective duration judgment as a function of age (see Figure 4). Using a reproduction time-estimation method (in which a person delimits a subsequent duration to be subjectively equal to a previously experienced duration), Kelley (1980) and Vanneste and Pouthas (1995) found that by about age 65 the mean duration judgment ratio was approximately 60–70% of what it was at age 20. These retrospective adult results are in agreement with Rosenberg's (1979) prediction. Unfortunately, no researchers have systematically studied retrospective duration judgments in children and adolescents below about 20 years of age.

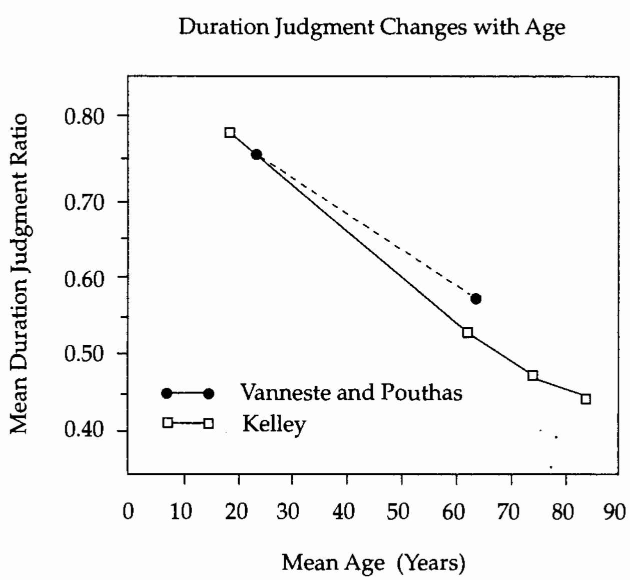

Figure 4. Using a reproduction time-estimation method, Kelley (1980) and Vanneste and Pouthas (1995) found that the duration judgment ratio decreases during the adult years.

Why do prospective and retrospective studies show opposite results? They involve inherently different mechanisms, with prospective judgments mainly influenced by attention and retrospective judgments mainly influenced by memory (see Block & Zakay, 1997, for a review). For example, decreasing the processing load (e.g., the number of stimuli presented during the target duration) shortens retrospective duration judgments but lengthens prospective duration judgments. Therefore, it is not surprising to see opposite results when processing rates decline. In addition, retrospective duration judgments lengthen to the extent that there are more changes in cognitive context. Thus, although the experience of duration in passing lengthens if a time period is relatively "empty," the experience of duration in retrospect lengthens to the extent that a time period is relatively "filled" with varying contextual changes (see Block & Zakay, 2001, for a recent review).

Correlation between Duration Judgments and Information-Processing Rate

Examination of the data suggests that information-processing rates may be involved in age-related changes in retrospective duration judgment if not the developmental changes. In order to compare duration judgment data and information-processing data, it is necessary to compare the duration judgment ratio at any given age as a percentage of that at age 20, the age of presumed maximum performance. Although data to date are meager, it is apparent that the adult age-related change in retrospective duration judgments resembles that noted for overall information-processing rates. After age 20, both information-processing rates and retrospective duration judgments decrease. Retrospective studies prior to age 20 are needed in order to suggest an even tighter association between the information-processing rates and retrospective duration judgment.

The information-processing rate may mainly reflect perceptual and motor speed, whereas the retrospective duration judgments may more heavily reflect memory processes. Nevertheless, there may also be some similarity in the underlying causes of the age-related changes. Clearly, no single hypothesis can account for all developmental and aging differences in duration judgments. Nevertheless, information-processing rate may be an important factor to consider in understanding age-related changes in time experience. Recent evidence, in fact, suggests that age-related changes in both memory and information-processing rate may be needed to explain age-related changes in time estimation (Perbal et al., 2002). More developmental and aging studies of retrospective duration judgment are clearly needed.

Chunking

Shortly after the discovery of the relationship between information and reaction time, Miller (1956) noticed an interesting connection between perceptual classification and memory. He claimed that people perceive and remember information in terms of learned units, which he called *chunks*. A chunk may be a binary digit, a decimal digit, a familiar word, or even a well-known saying. In other words, human information depends on chunks, not on bits of information. In mathematics and physics, the number of bits processed per second is a system's information-processing rate. In psychology, however, most evidence indicates that chunks (meaningful units) instead of bits (mathematical units) are critical in human information processing and memory (Halford, Wilson, & Phillips, 1998). Because psychological time is more intimately related to processes involving perception and memory than it is to processes involving reaction time, we will need to consider chunk-rate as well as bit-rate as an index of human information processing as applied to the experience of time. As a person ages, the person may gain knowledge that would enable the processing of information in relatively larger chunks. One result of this may be that long-term episodic memory contains information that is more highly organized. If this is the case, retrospective duration estimates may decrease (Ornstein, 1969). In short, if older adults are able more efficiently to chunk information in relatively large units (each containing more bits of information), this may be yet another factor that leads to the reported shortening of duration experience in retrospect.

Measuring Life's Duration by Information Processed

The duration of an organism's life can be measured by either the chronological age or the total amount of information processed (somewhat like one's cumulative number of thoughts). People may prefer to measure life's duration by the amount of information (bits) processed in their lifetime – the *bit count*. For example, a person could conceivably be 30 years old and yet have processed more information than someone who has lived 60 years. Chronological age for that person would be a less meaningful reflection of life's duration than the total bit count. Physical time (referred to as *proper time* by physicists) would not be a good scale of time for what the person subjectively experiences.

If we stop to wonder where this notion came from we do not have to look any further than the automobile. As opposed to people, cars are judged not only by the year they were manufactured but also by

their mileage. The mileage of a car would seem to be the counterpart to the total information processed by humans. Although it is not possible at this time to measure the total information processed for an individual human, in principle it is possible.

Curiously, humans do not attempt to estimate their bit age. In part, this is because they cannot measure their own information-processing rate, and because they certainly cannot calculate their lifetime bit count. They can and do, however, recognize that they slow (both physically and mentally) with age. They may even recognize that their information-processing rate (as measured by reflex rates, for example) declines with advancing age. Instead of estimating the length of their life by summing their activities (cerebral or physical), humans choose to compare their current activity level to that when they were younger or to someone else who is younger. Thus, a 60–year-old may feel that his or her reflexes are as quick as that of a 50–year-old. Humans do not measure life's duration in terms of their total activities or total energy expended or total information processed, perhaps because it is logistically impossible to do so at the present time.

Prolonging Subjective Duration and Longevity

One possible conclusion from these analyses is that human longevity may be increased by directly manipulating the information-processing rate. Davies (1994) summed it up by proposing that there are two ways to prolong human longevity. One way is to survive as long as possible (i.e., to increase chronological age). The other way is to look for a means to speed up thinking and experiencing (i.e., to increase the information-processing rate and consequently the bit age). This conclusion implies that physicians should not only be looking for ways to prolong the chronological age of humans but also for ways to increase their information-processing rate.

At this time, there are no dramatic ways to increase the information-processing rate. Drugs such as caffeine are known to increase the information-processing rate, as well as to alter duration estimates (Botella, Bosch, Romero, & Parra, 2001; Gruber & Block, 2003; Stine, O'Connor, Yatko, Grunberg, & Klein, 2002). These effects, however, are relatively small. Other, more powerful drugs such as metamphetamine produce more major changes, but they are also dangerous. Perhaps the only safe and successful treatment, although difficult with which to comply, is that of dietary restriction. A substantial reduction of one's total caloric intake (up to 40%) has repeatedly been shown to increase chronological longevity in animals and some humans. Along with that improved longevity, an increase in the information-processing rate has also been observed. Animals on dietary restriction exhibit shortened latencies in maze learning, which reflects an increased information-processing rate (Means, Higgins, & Fernandez, 1993).

Assuming that it will one day be possible, what is the limit to which human information-processing rate should be raised? Humans have genetically programmed homeostatic mechanisms to maintain physiological parameters (e.g., pH, temperature) within certain ranges. They do not function as well outside those ranges. For that reason, humans may not function well at ultra-high processing rates. The maximum desirable information-processing rate is probably that which occurs when the individual was at his or her peak (about age 20). Therefore, assuming that information-processing rates can be increased greatly some day, the maximum desirable bit age should probably not be raised higher than the corresponding chronological age. Under those circumstances longevity would be maximum, and time would probably not seem to pass as quickly (Flaherty, 1999).

However, retrospective duration judgments depend not only on the information-processing rate but also on episodic memory for events and changes in cognitive context during the time period (Block & Zakay, 1997, 2001). Studies on retrospective duration judgment suggest a possible way to decrease the subjectively fast rate of passing of time that accompanies aging. If an older adult chooses to engage in varied activities that lead to increased changes in cognitive context, he or she will remember time periods of life as being relatively long. The simplest way to prolong apparent longevity, therefore, may be to avoid routines and uneventful activities and to seek changes and eventful activities.

Conclusions

The notion that subjective time is related to information processing involves two assumptions: (a) Subjective time is based upon the overall information-processing rate, and (b) the subjective experience of life's duration is based upon the total information processed (cumulative uncertainty).

Age-related decreases in information-processing rate (along with such additional factors as decreases in body temperature, difficulties in dividing attention, and enhancements in chunking) are probably responsible for the "quick passage of time" that older adults typically report.

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