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Subjective Time vs. Proper (Clock) Time

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Introduction

The notion that subjective time is related to information-processing, introduced a hundred years ago by psychologists, has in recent years received support from some cosmologists. It involves *two assumptions: (1) subjective time is based upon the overall information-processing rate, and (2) the subjective experience of life's duration is related to if not based upon the total information processed (cumulative uncertainty).*

This suggests that an age-related decline in human information-processing rate is at least partly responsible for the "quick passage of time" that is associated with aging. It also suggests that life's duration (and longevity) can in principle be measured either by chronological age or the total information one has processed. To explore these hypotheses, we analyzed the available data involving age-related information-processing rates and time estimation (duration judgment) studies. We also discuss one of the most profound implications of the hypothesis, that human longevity can be increased not only by increasing chronological age but also by increasing the information-processing rate and thereby the total information processed.

Hypotheses from Cosmology

Open Cosmology Theory

Like some psychologists a few cosmologists believe that subjective time and life's duration are based upon human information processing rate and the total information processed. Thus, the faster one processes information and the more information one accrues the more one has experienced in life and the greater will be the subjective experience of time for those events. Conversely, if a person processes little information there will be little subjective experience of time having passed.

Based on those assumptions and the validity of the open-cosmology theory (in which the universe will forever continue to expand) Dyson[1] predicted that as the temperature of the universe approaches absolute zero, any sentients (humans in the future) will experience a dramatic decrease in their information-processing rate. Consequently, time will seem to pass so rapidly for them that a year might seem like minutes. Sentients living under these conditions will experience their life to be very short compared to their chronological ages. Because there is a finite amount of energy for a sentient civilization, Dyson suggested that sentients should hibernate in order to prolong their chronological ages. This way at least a sentient's chronological age, if not the experienced lifespan, could be increased.

Krause and Starkman[2] agree with Dyson that life's duration is ultimately based upon the total information processed. However, they disagree that hibernation is enough to prevent the extinction of all information processing systems and the therefore the demise of civilization.

Dyson calculated the change in subjective time as the temperature of the universe decreases using the following function, assuming a scaling law in an open cosmological model:

$$u(t) = f \int_0^t \theta(t')dt'$$

where u(t) is subjective time, f is a scale factor, and $\theta(t')$ is the temperature of the sentient. Note, however, that this equation applies only to a conglomerate of sentients, not to any individual sentient.

As the temperature decreases to near absolute zero in an open universe, sentients of the future will have to adapt. It is assumed that efforts to maintain their normal body temperature will ultimately be futile. They may have to replace all their bodily parts with temperature-resistant materials if they do not wish to freeze. From a physics viewpoint, this scenario is possible.

Closed Cosmology Theory

A closed-cosmology theory proposes that the universe will not expand forever, but will collapse. Based on this assumption, Tipler and Barrow[3] predicted the opposite of what Dyson[1] predicted: As the universe collapses and its temperature approaches infinity, sentients will experience a dramatic increase in their information-processing rate and consequently in their subjective time. As the information-processing rate approaches infinity in the last three minutes of the universe, sentients will be processing information at such a high rate that their subjective time will be infinitely long. The experienced lifespan for these sentients will be enormous, completely out of proportion to their chronological ages. Sentients living in the last three minutes will therefore experience immortality (infinite longevity) as the universe ends.

Tipler and Barrow went on to suggest that as the information-processing rate of future sentient beings increases relative to clock time (or proper time as physicists prefer to call it), the contrast between proper time and subjective time will be striking. As a result of the discrepancy between proper time and subjective time, sentients presumably will not hesitate to reject proper time as the appropriate measure of time. In the current astrophysical environment, proper time is presumably accepted as the appropriate measure of time because the information-processing rate of humans is directly proportional to proper time. In other words, one second of subjective time corresponds fairly well with one second of proper time.

These two cosmological hypotheses were profound in that they suggested that proper time is not the only important time in physics and biology. For what was arguably the first time, physicists were beginning to acknowledge that subjective time is important, although perhaps not until sentients' information-processing rate is drastically altered. Although the open- and closed-cosmology scenarios are speculative and their predictions are opposite, the assumptions about subjective time are similar.

Hypotheses from Psychology

Prior to the hypotheses of the physicists, Guyau[4] and James[5] were two of the first theorists to relate time experiences to the concept of human information processing in an attempt to explain the phenomena of subjective time. Although neither of them used the term information processing or level of uncertainty, they 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. John

Michon[6] also noted the circumstances under which time is the product of information processing.

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. The shorter the latency of the person's response or the more bits (or chunks) a person processes during a time period, the faster is the person's information-processing rate. 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[7]. However, for our purposes, we can conveniently ignore the difference between bits and chunks.

It would appear that the cosmological hypotheses have no relevance to human beings in this epoch because they deal with catastrophic changes in information-processing rates. However, it has been known for many decades that such factors as temperature and age influence the human information-processing rate. For this reason, there is a parallel to what the cosmological hypotheses propose about changes in sentients' subjective time and subjective lifespan as the universe evolves. Evidence from studies of subjective time may clarify the physics hypotheses.

Information-Processing Rate and Temperature

Past psychological studies do seem to link a person's subjective time to his or her information-processing rate. Hoagland [8] reported that he went to the drugstore to get some medicine for his wife, who had a fever of 104• F. 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[9]. 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[10]. Siffre[11], a young geologist, lived for two months alone in a cave on a floor of melting ice in near-freezing conditions. He suffered from near-hypothermia, a condition of semi-hibernation, and experienced time to pass very slowly. He estimated that he had been in the cave for only about four weeks. Decreased body temperature also leads to a decrease in a person's information-processing rate[12].

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[13]. When tested retrospectively, however, duration judgments decrease when body temperature falls by as little as 1.0• F. [14].

Information-Processing Rate and Age

It has been commonly accepted since ancient times that subjective time changes with age. Rosenberg[15], a neurologist, theorized that the seemingly more rapid passing of time as a person ages may be attributed, at least in part, to changes in the person's information-processing rate. The effect that age has on the information-processing rate has never been in question. For a variety of information-processing tasks (verbal and visuospatial), the mean information-processing rates increase from birth and reach a maximum[20] at about age 20. They decline from that point on, as Lawrence, Meyerson, and Hale[17] found. The mean processing scores for both verbal and visuospatial tasks at any age is best appreciated by expressing it as a percentage of that noted at about age 20, the age of maximum performance. At age 10, the mean information-processing rate is about 61% of what it will be at age 20. At age 60, the mean verbal and visuospatial information-processing rate drops to 50% of that value (Figure 1).

However, the literature on age-related changes in subjective time has been more controversial. Although many psychologists have asserted that subjective time seems to accelerate as a person ages, specific studies to measure the extent of that acceleration (in terms of years) did not begin until relatively recently. Lemlich[18] asked people of various ages to indicate how much slower or faster the year 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.

Most investigators of subjective time have looked at shorter durations (on the order of seconds and minutes) because the estimation of years is difficult and subject to many idiosyncrasies. In two meta-analyses, Block, Zakay, and Hancock[19, 20] noted that prospective time estimates change from age 10–72. In Figure 2, 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[15] had predicted. However, the findings probably reflect the opposite effects that are often obtained in the prospective and retrospective paradigms;[21] these data all came from a prospective paradigm.

Retrospective time-estimation studies show different results. Only two research groups have reported the results of studies on retrospective duration judgment as a function of age (see Figure 3). Using a reproduction time-estimation method (in which a person delimits a subsequent duration to be subjectively equal to a previously experienced one), Kelley[22] and Vanneste and Pouthas[23] found that by around 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 the Rosenberg[15] prediction. Unfortunately, there are no retrospective studies prior to age 20 yet.

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 (recollection of bits of information).* 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[21]. Therefore, it is not surprising to see opposite results when processing rates decline. On the other hand opposite results are not necessarily seen in long-term duration judgments and is most evident in patients who exhibit amnesia. H.M., the famous victim of post-surgical anterograde amnesia exhibited decreased (not increased) prospective duration judgments when tested in the range of 30-300 seconds[24]. Thus, it would appear that whereas opposite results may be seen in short term duration studies (wherein the target duration is usually less than 30 seconds), they may not always be seen in long term duration studies (prospective and retrospective) wherein episodic memory is involved.[25]

Correlation Between Duration Judgments and Information-Processing Rate

Examination of the data suggests that information-processing rates may be involved aging 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 is 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, the information-processing rate may be an important factor to consider, particularly in the retrospective studies. More developmental and aging studies of retrospective duration judgment are clearly needed.

Duration judgments may turn out to correlate well with information-processing rates in these studies. However, body temperature does not do so. Changes in information-processing rates with aging are probably more a result of brain deterioration[26] than a brain temperature decrease. Furthermore, body temperature (and basal metabolism) does not peak at age 20; it decreases monotonically across the lifespan[27]. Thus, changes in subjective time over the lifespan are not likely to be solely a result of body (i.e., brain) temperature changes.

Cosmological Versus Current Environment

Subjective Time in Cosmology Versus Subjective Time in Psychology

Subjective time in cosmology focuses only on the bit rate and the total bit count. In fact, the subjective time of physicists is for all intents ands purposes the same as the bit count. Subjective time in psychology, on the other hand, is influenced by many factors. Most notable is the distinction that needs to be made for prospective and retrospective duration judgments. Prospective duration judgments for short term intervals is not what cosmologists are talking about when referring to "subjective time." The subjective time of the cosmologists refers to retrospective time, in particular long-term duration judgments (more than 30 seconds).

Recalibrating Versus Abandoning Subjective Time

It is important to examine a few issues that relate to the assumptions and predictions of the physics hypotheses. One prediction is that sentients will not hesitate to reject proper (clock) time as the appropriate measure of time when it decelerates relative to subjective time[3]. However, the notion that sentients living in the very cold stages of an open universe will reject proper time assumes that they will not be able to recalibrate to compensate for the gradual changes. Sentients may instead recalibrate their subjective time to adapt to the gradual changes in their timekeeping processes and rates. There is evidence that the continual recalibration of subjective time to proper time can occur. In estimating durations, humans compare some currently accumulated temporal "pulse count" with pulse count totals (stored in a reference-memory store) that accumulated during earlier, similar time periods[28,29]. Therefore, if there is a gradual change in the rate of a pacemaker, which is producing the pulses (perhaps because of a gradual brain temperature change), people experience and judge a duration much the same way they did before the gradual change.

However, it is far from certain that recalibration is always possible particularly when there is a sudden change in rates. For example, a sudden change in the rate of a pacemaker ("pulse rate") may lead to a markedly altered time experience. Binkofski and Block[30] described the case of a man with a brain tumor which apparently slowed his internal clock and, hence, his information-processing rate. The effects were surprisingly sudden and dramatic. He experienced normal environmental events as occurring very rapidly, much like a videotape played on fast forward. He could not even tolerate watching television, because the progression of events was too quick for him to follow. Perhaps because his information-processing rate was suddenly and drastically slowed, he also greatly misjudged a one-minute duration.

There is other compelling evidence that recalibration may not always be possible. As mentioned many times, duration judgment (both prospective and retrospective) is a function of age. If calibration for humans was successful we should expect no age related changes. The overall evidence suggests, therefore, that recalibration cannot be relied upon.

Currently, we humans do not abandon proper time for subjective time despite the fact that short-term retrospective time estimates decline slightly with aging. Perhaps that is because of the variability of subjective time. Perhaps that is because many factors (e.g., boredom) influence subjective time, causing people to regard subjective time as an illusion, and the time of physics (proper time) as "real." However, humans might not abandon subjective time if they recognize that one of the basic mechanisms on which it is founded, the information-processing rate, is "real."

Measuring Life's Duration by Information Processed

One of the assumptions of the physics hypotheses[1,3] is that the subjective experience of life's duration can be measured either by the chronological age or the total amount of information processed (somewhat like one's cumulative number of thoughts). They suggested that sentients may prefer to measure life's duration by the amount of information (bits) processed in their lifetime – the *bit count*. For example, in the closed cosmology scenario, a sentient could conceivably be 10 years old and yet have processed more information than someone in this epoch who has lived 100 years. Chronological age for that sentient would be a less meaningful reflection of life's duration than the total bit count. Proper time would not be a good scale of time for what the sentient 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. It is possible, however, possible to measure it for a population of humans.

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 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 4). 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 are far from being able to make these calculations for individuals.

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 reflexes are as quick as that of a 50 year-old. But, humans do not measure life's duration in terms of their total activities or total energy expended or total information processed. But that is only because it is logistically impossible to do so at this time.

Prolonging Longevity by Two Methods

The most profound prediction of the above hypotheses is that human longevity may be increased by directly manipulating the information-processing rate. Davies[31] summed it up by proposing that there are two ways to prolong the longevity of sentient beings. One way is to survive as long as possible—i.e., to increase proper time or chronological age. The other way is to look for a means to speed up thinking and experiencing—that is, to increase the information-processing rate (and consequently the bit age). Thus, these hypotheses imply 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[32], as well as altering duration estimates[33]. The effect, however, is minor. 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.[34]

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 within certain ranges. They do not function as well outside those ranges, e.g. pH, temperature. 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 (around age 20). Therefore, assuming that information-processing rates can be increased ad libitum 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 fly"[35] as much. However, the "quick passage of time" should not be expected to completely abate because retrospective duration judgment is dependent not only upon the information-processing rate but also upon episodic memory.[36] Until the problem of declining memory with aging is also resolved, duration judgment issues will still remain.

Summary and Conclusions

The notion that subjective time is related to information-processing, introduced by psychologists, has also received support from cosmologists. It involves two assumptions: (1) subjective time is based upon the overall information-processing rate, and (2) the subjective experience of life's duration is based upon the total information processed (cumulative uncertainty). With aging, the total amount of uncertainty in the situations that a person has encountered increases, and this is related to the total amount of information processed.

For some cosmologists this means that as the temperature of the universe changes, information processing rates (and uncertainty level) of future sentients will change drastically resulting in dramatic changes in subjective time. For psychologists this means that the age-related decline in human information-processing rate is partly responsible for the "quick passage of time."

In two meta-analyses of prospective time, duration-judgment exhibited a nonmonotonic (U-shaped) function over the lifespan, opposite of what the psychological hypotheses predicted. However, in adult retrospective time studies, duration judgment declined with age, thereby providing some support for the association between subjective time and information-processing rates.

We also discuss a profound implication of the hypothesis, that human 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 level of uncertainty.

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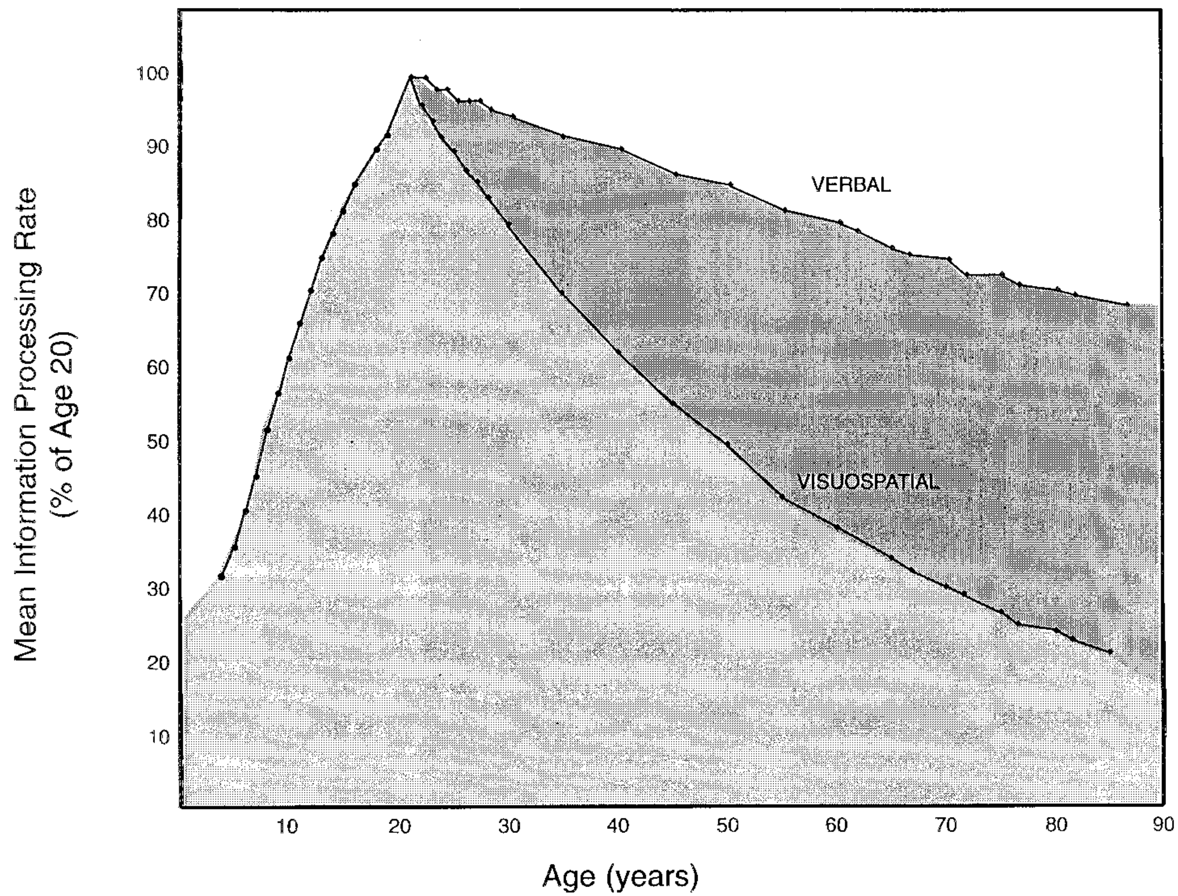


Figure 1. The mean information-processing rate (of verbal and visuospatial information-processing tasks) increases from birth and reaches a maximum at about age 20. The processing rate at any age is expressed as a percentage of that at about age 20, the age of maximum performance. Data are taken from Kail (1991) and Lawrence et al. (1998).

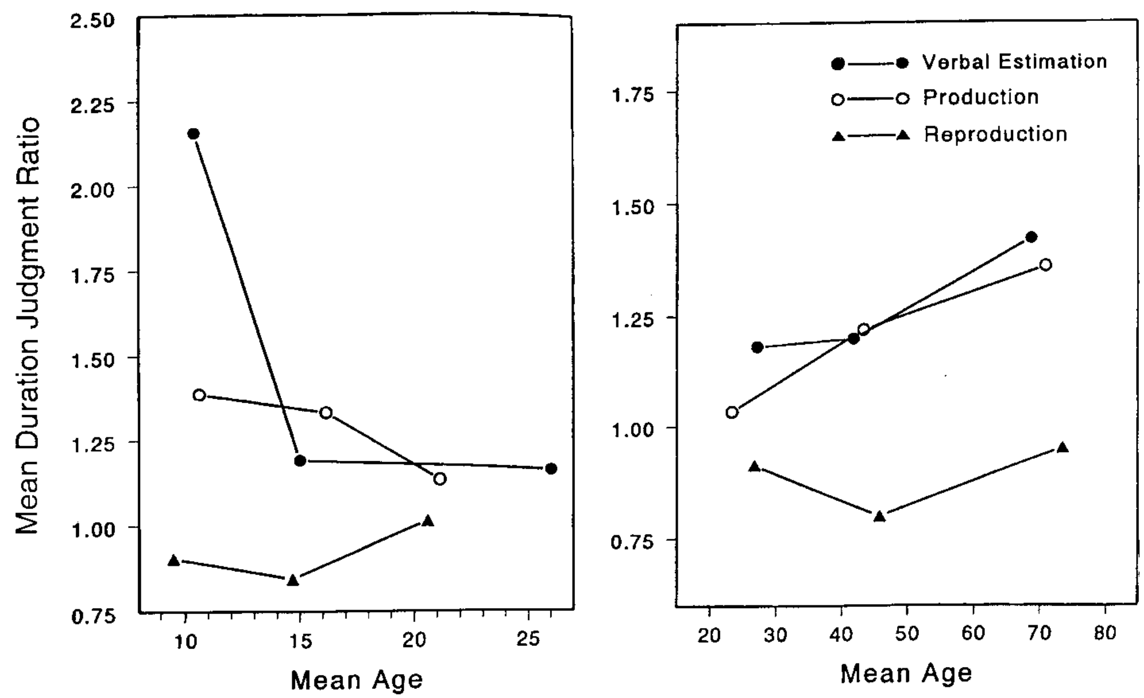


Figure 2. In two meta-analyses, Block and Zakay (1998, 1999) noted the change in prospective time estimation from age 10–72. The duration-judgment ratio (the ratio of the subjective to objective time) is plotted as a function of age. The results varied depending on the method of testing.

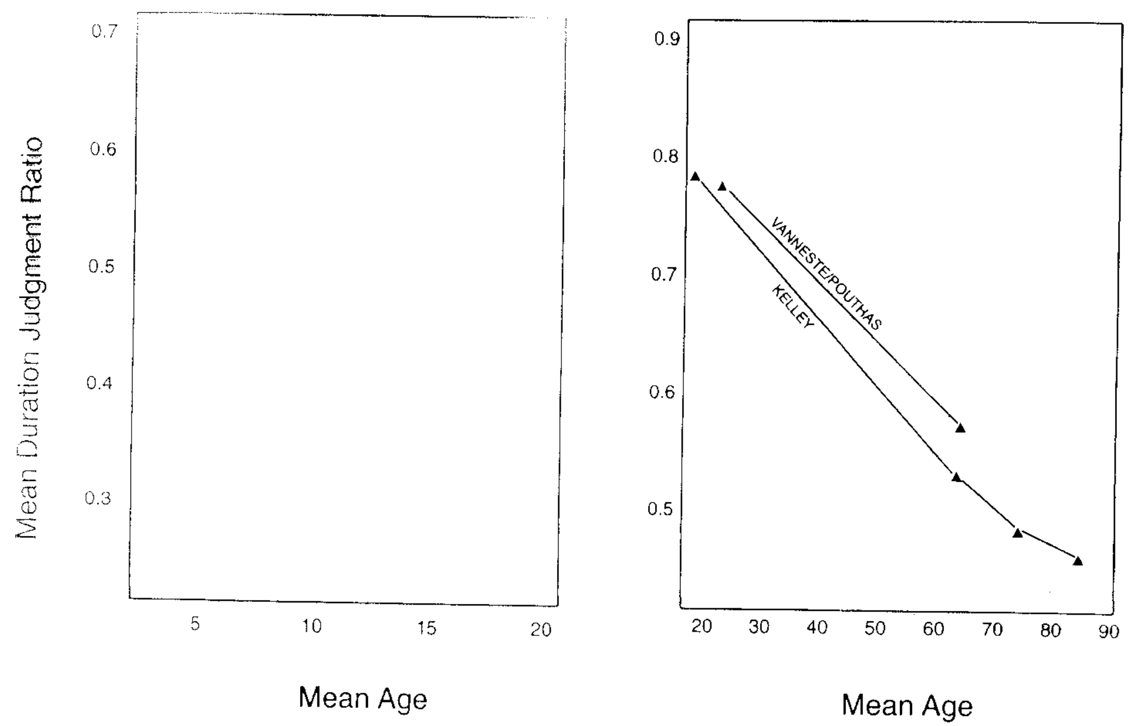
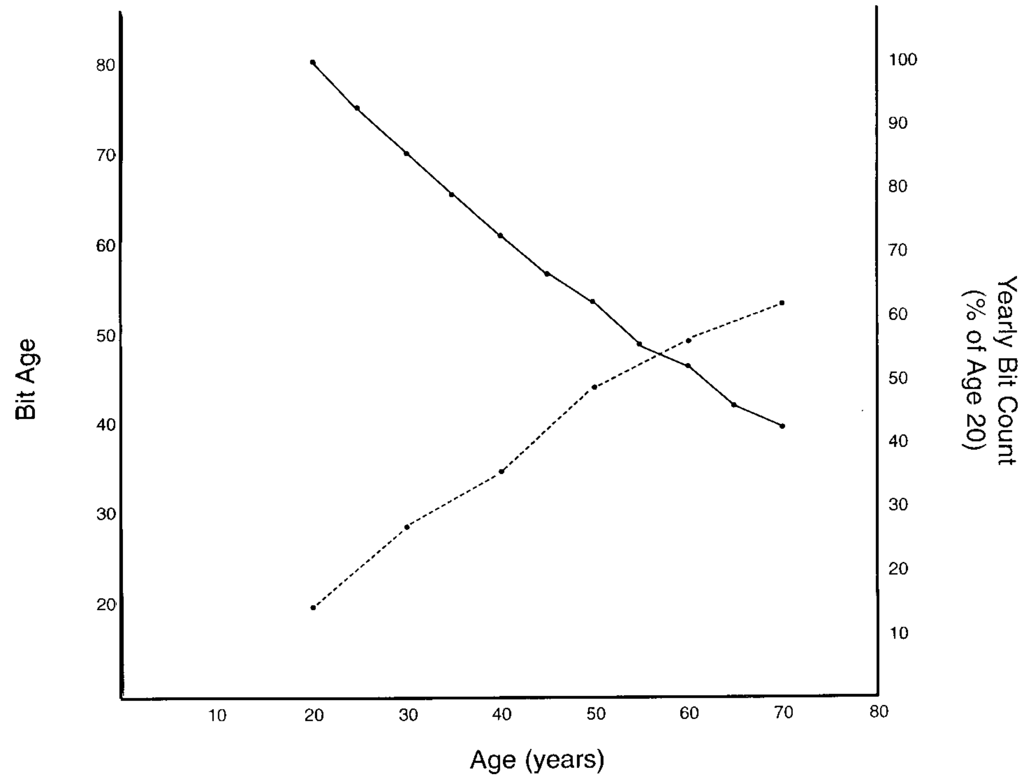


Figure 3. Using a reproduction time-estimation method, Kelley (1980) and Vanneste and Pouthas (1995) found that the duration-judgment ratio decreases during the adult years.



<u>Figure 4</u>. 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.