

3311 cm^{-1} , with no absorption in the 3600 cm^{-1} region, indicated acetylation of the alcohol and not of the acetylenic group.

The proton magnetic resonance spectrum (13) of the metabolite in D_2O was compared to that of 1 in a mixture of CD_3OD and D_2O (1:1). The ethyl and the vinyl chloride groups were intact, but the acetylenic proton was absent. The presence of a multiplet (4H), 3.1 to 3.8 ppm (δ), and a doublet (1H), 4.7 ppm, $J = 7.7$ Hz, in the metabolite spectrum suggested a sugar moiety in the β conformation, as is normally the case for naturally occurring glucuronides.

All of the spectral data support the assignment of structure 3 to the major metabolite. Furthermore, our inability to demonstrate hydrolysis of the metabolite with β -glucuronidase is consistent with the observation (2) that the C-glucuronides of phenylbutazone and sulfinpyrazone are not substrates for the enzyme.

The identification of three types of C-glucuronides in mammalian systems suggests the possibility that many unidentified polar metabolites that are not hydrolyzed by β -glucuronidase may, in fact, be products of C-glucuronidation. This raises interesting questions regarding the specificity of the enzymes responsible for glucuronidation and the mechanisms by which they function.

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6. The instrument was a Waters Associates liquid chromatograph; pump model M6000A, injector model U6K, and detector model 440, dual wavelength. Waters μ Bondapak C_{18} reverse-phase columns were used.
7. An AEI model MS-12 single-focusing mass spectrometer was used to obtain the electron impact spectra. A modified model MS-902 double-focusing mass spectrometer, equipped with a direct inlet system, was used for chemical ionization spectra. Reagent gas was isobutane at a pressure of 0.5 torr.
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11. Determination of the chemical ionization mass spectrum at high resolution gave an MH^+ ion m/e 623.2452, which corresponds to the formula $\text{C}_{26}\text{H}_{50}\text{ClO}_7\text{Si}_4$ (calculated m/e , 623.2478).
12. The infrared spectrometer used was the Nicolet, model 7000 P, with Ge-KBr beamsplitter and liquid nitrogen-cooled detector. Samples were run as dilute (0.3 to 0.5 mg/ml) solutions in spectral-grade carbon tetrachloride; a 1-cm pathlength cell with calcium fluoride windows was used.
13. Proton magnetic resonance spectra were ob-

tained with a Varian XL-100 spectrometer provided through NIH grant 00892-1A1 from the Division of Research Resources.

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Critical-Path Scheduling of Mental Processes in a Dual Task

Abstract. *Scheduling theory is used to extend the additive factors method of analyzing reaction times to tasks involving concurrent processing. Data indicate that mental processes in a double-stimulation experiment by Becker are executed in a critical-path network. A relationship predicted for the timing of the responses of the task is shown to hold.*

When a set of mental processes, such as perceiving and deciding, must be executed to perform a task, the brain must resolve the same problem as that faced by computer operating systems and industrial managers, namely, how to schedule the many activities demanding attention. The problem is treated in the theory of scheduling (1). If this theory applies to mental processes, certain predictions follow for reaction times.

The primary technique for analyzing reaction times is Sternberg's additive factors method (2). Its usefulness is limited, though, mainly to tasks in which all processing is sequential. But concurrent processing is likely and of much theoretical interest since Townsend (3) has shown that both kinds of processing often yield the same reaction time distributions. Tasks incorporating both kinds of processing can be analyzed if Sternberg's method is combined with ideas from scheduling theory.

With the additive factors method, two experimental factors that increase reaction time are manipulated. Suppose (i) all the processes of a task are executed in a sequence and (ii) each factor prolongs a different process. The effect on reaction time of prolonging both processes will be the sum of the effects of prolonging them individually. A violation of additivity has usually been interpreted in the framework of the method as indicating that (ii) is false. But nonadditivity might indicate instead that (i) is false, that processing is not entirely sequential. Nonadditivity turns out to be likely when separate processes are prolonged in a task involving concurrent processing. For such a task, of course, there is no reason to expect the principles of the additive factors method to apply without modification.

The modifications presented here are

based on critical-path scheduling (1), which allows both sequential and concurrent processes to occur. The technique requires only that the processes be partially ordered, that is, that they can be represented by a directed acyclic network (Fig. 1).

As the critical-path method is ordinarily used, the network is given, and the time required to complete the task is to be calculated. The psychologist has the opposite problem of knowing the time required to complete the task under various conditions and wanting to reconstruct the unknown network. The key to constructing the network is to use the idea from the additive factors method of prolonging processes. The effects of such prolongations are surprisingly informative about the network.

In a double-stimulation experiment by Becker (4), two factors have additive effects, but there is evidence that the underlying network is more complicated than a simple sequence of processes. In the experiment, the digit 1 or 2 was presented visually, and, after an interval of either 90 or 190 msec, a tone of high or low frequency was presented. On each trial the subject pressed a button with one hand to indicate which digit occurred and another with the other hand to respond to the tone. In one condition the subject pressed the same button for either tone, and in another condition he chose one of two buttons to indicate which tone occurred.

Table 1 gives the increases in response times produced by changing the experimental conditions. Departing from custom, I express response times for both responses measured from the onset of the first stimulus, the digit. Response times in the condition with one tone response choice and 90 msec between stimulus onsets are baselines from which

Table 1. Increases in response times when processes are prolonged in Becker's experiment (4). Response times to both stimuli were measured with respect to the first stimulus, the digit. Increases were calculated with respect to the baseline response times of 346 msec for the digit and 475 msec for the tone.

<i>I</i> (msec)	Tone choices	Prolon- gations	Increases (msec)	
			ΔT_d	ΔT_n
90	1	Baseline	0	0
190	1	($\Delta I, 0$)	21	37
90	2	(0, ΔN)	87	145
190	2	($\Delta I, \Delta N$)	113	182

the increases are calculated. Increasing the number of response choices to the tone is assumed to prolong a process, N , by an amount ΔN . The interval between the onsets of the stimuli, I , is prolonged by $\Delta I = 100$ msec when it is increased to 190 msec.

Let $\Delta T_d(\Delta I, 0)$ denote the increase in response time to the digit when I is prolonged by ΔI , with N unchanged; $\Delta T_d(0, \Delta N)$ and $\Delta T_n(\Delta I, \Delta N)$ are defined analogously. The effects of prolonging I and N are additive. For the digit response time increases,

$$\Delta T_d(\Delta I, \Delta N) = \Delta T_d(\Delta I, 0) + \Delta T_d(0, \Delta N)$$

that is, 113 msec \approx 21 msec + 87 msec (Table 1). Similarly, for the tone response time increases, ΔT_n , 182 msec = 37 msec + 145 msec.

The additivity shows that I and N are sequential processes. Since sequential models are ubiquitous, it is worth seeing why all the processes in the task cannot be sequential. If the processes were all in a sequence, when I is prolonged every process following I should be delayed by the amount of the prolongation. Hence the response times should be increased by this amount also. But, when I is prolonged by 100 msec, the tone and digit response times are each increased by much less (Table 1).

This fact is easily explained by a network model. Processes in a network are related in one of two ways. Those joined by a directed path (for example, I and N in Fig. 1a) must be executed in order and are called "sequential." Those not joined by a directed path (such as I and U in Fig. 1a) can be executed concurrently with each other, and are called "independent." No process can begin until all those preceding it are finished. Every process has a duration, and the duration of the task, the response time, is the sum of the durations of the processes on the longest path through the network, called the "critical path."

The increase in response time produced by prolonging two processes depends on whether they are independent or sequential. Let T denote the response time when all the processes are at the shortest durations used in the experiment. Let $\Delta T(\Delta X, 0)$ denote the increase in T produced by prolonging process X by ΔX , leaving Y unchanged; other increases are denoted analogously. It can be shown (5) that if X and Y are independent,

$$\Delta T(\Delta X, \Delta Y) = \max\{\Delta T(\Delta X, 0), \Delta T(0, \Delta Y)\} \quad (1)$$

The situation is more complicated if X and Y are sequential. Suppose X precedes Y . The amount of time by which X can be prolonged without making Y start late is called the "slack" from X to Y , written $S(XY)$. Similarly, the amount of time by which X can be prolonged without delaying the response, r , and thereby increasing the response time is called the "total slack" for X , written $S(Xr)$. A process is on a critical path if and only if its total slack is zero. If all the processes are in a sequence, there is only one path, necessarily critical, so every process has zero total slack.

Becker's experiment provides an example of slack. When the interval I was increased by 100 msec, the response times were increased by much less. According to a network analysis, part of the prolongation of I was used to overcome the slack, and only the remainder increased the response times. This can only happen if some sequence of processes is executed concurrently with I and terminates after I is finished (U in Fig. 1a; in Fig. 1a, I is between s_d and s_n , the onsets of the digit and tone, respectively).

Slack is important when two sequential processes are prolonged. Suppose X precedes Y on a path. If the prolongations ΔX and ΔY are not too small, it can be shown (5) that

$$\Delta T(\Delta X, \Delta Y) = \Delta T(\Delta X, 0) + \Delta T(0, \Delta Y) + K(XY) \quad (2)$$

where $K(XY) = S(Xr) - S(XY)$ is called the coupled slack from X to Y .

The magnitude of $K(XY)$ does not depend on the magnitudes of ΔX and ΔY . This fact provides a strong test of whether a network analysis applies to a given set of data: all values of ΔX and ΔY large enough for Eq. 2 to hold should yield the same value for $K(XY)$, the interaction term (6).

If all the processes are sequential, $K(XY) = 0$ for every pair X and Y , and Eq. 2 becomes the additive relationship

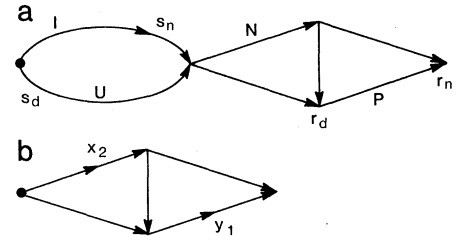


Fig. 1. Task networks. Each arrow represents a process. No process can begin until all those preceding it are finished. (a) Network for Becker's (4) experiment. Points s_d and s_n are the onsets of the digit and tone, respectively, and the corresponding responses are r_d and r_n . (b) If $K(XY) < 0$, the task network contains a Wheatstone bridge subnetwork; x_2 is the terminal point of X and y_1 is the starting point of Y .

of the additive factors method. In general, however, Eqs. 1 and 2 indicate that when two separate processes in a network are prolonged, their effects will interact.

A negative value of $K(XY)$ is very informative. If X precedes Y and $K(XY) < 0$, certain relationships hold among the path durations. Moreover, the task network must have a subnetwork homeomorphic to the one in Fig. 1b, called a Wheatstone bridge. In Fig. 1b, x_2 and y_1 denote the terminus of X and start of Y , respectively.

Experiments in which the subject makes two responses on every trial are also informative. Let the two response times be T_1 and T_2 , both measured from the same point. Each response time considered alone will satisfy Eq. 1 or 2 under the appropriate conditions. Furthermore, T_1 and T_2 are related. Suppose X precedes Y , and $\Delta T_1(\Delta X, 0)$ and $\Delta T_2(\Delta X, 0)$, the increases in T_1 and T_2 produced by prolonging X by ΔX , are both positive. Then (5),

$$\Delta T_1(\Delta X, 0) + K_1(XY) = \Delta T_2(\Delta X, 0) + K_2(XY) \quad (3)$$

If instead Y precedes X , then $\Delta T_1(0, \Delta Y)$ and $\Delta T_2(0, \Delta Y)$ are required in Eq. 3 in place of $\Delta T_1(\Delta X, 0)$ and $\Delta T_2(\Delta X, 0)$. The order of X and Y is revealed, then, if one version of Eq. 3 holds but not the other. If neither version holds, a network model is invalid.

In Becker's experiment (4) the additive effects of prolonging I and N are described by Eq. 2 for both the digit and tone response times, with coupled slacks $K_d(IN) = K_n(IN) = 0$. Equation 3 shows that I precedes N because from Table 1, $\Delta T_d(\Delta I, 0) + K_d(IN) = \Delta T_n(\Delta I, 0) + K_n(IN)$; that is, 21 msec \approx 37 msec, and the error is 16 msec. If we assumed the opposite order, N preceding I , Eq. 3 be-

comes $\Delta T_d(0, \Delta N) + K_d(IN) = \Delta T_n(0, \Delta N) + K_n(IN)$, but this is false since 87 msec \neq 145 msec; the error would be 58 msec.

Briefly, the rest of the network for Becker's experiment is constructed as follows. Let r_d and r_n denote the responses to the digit and the tone, respectively. The subject was instructed to respond to the digit before responding to the tone. This constraint can be represented by a process P between r_d and r_n , having, perhaps, zero duration. We will show that $K_n(NP)$ is negative, so that N and P are in a Wheatstone bridge. Since $\Delta T_d(0, \Delta N) = \Delta N - S(N, r_d)$ and $\Delta T_n(0, \Delta N) = \Delta N - S(N, r_n)$ we have

$$\Delta T_d(0, \Delta N) - \Delta T_n(0, \Delta N) = S(N, r_n) - S(N, r_d) = -58$$

But since $S(NP) = S(N, r_d)$ (Fig. 1a),

$$S(N, r_n) - S(NP) = K_n(NP) = -58 < 0$$

Additional details are provided in (7).

I have sketched a method here for determining, at least in part, the schedule of processes the brain uses for a particular task. This method of analyzing reaction times considers more complicated arrangements of processes than most previous ones and yields more information. The next question, no doubt much harder, is Why does the brain choose the particular schedule it uses?

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6. Conceivably, a subject could produce constant values of $K(XY)$ through speed-accuracy trade-offs in the various conditions, but such a strategy is unlikely to succeed. The speed-accuracy trade-off phenomenon suggests an interesting question: Given an empirically determined speed-accuracy (or time-cost) function for the entire task, characterize the class of possible speed-accuracy functions associated with the component processes.
7. R. Schweickert, in preparation.
8. I thank B. Kantowitz, J. Neely, J. Solberg, and J. Townsend for helpful suggestions.

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Visually Induced Self-Motion Sensation Adapts Rapidly to Left-Right Visual Reversal

Abstract. After 1 to 3 hours of active movement while wearing vision-reversing goggles, 9 of 12 (stationary) human subjects viewing a moving stripe display experienced a self-rotation illusion in the same direction as seen stripe motion, rather than in the opposite (normal) direction. This result indicates that the neural pathways which process visual self-rotation cues can undergo rapid adaptive modification.

Visual and vestibular motion cues contribute to self-motion perception in a complementary fashion (1). In everyday life, head rotation results in an equal and oppositely directed angular motion of the visual scene relative to the head. This association between normal active head rotation and relative scene motion is believed to account for the phenomenon of "circularvection" (CV) (2): a pattern of stripes rotating around a stationary observer soon elicits a compelling sensation of self-rotation in the opposite direction (3).

When human subjects wear optics which either "mirror" reverse vision from left to right or invert it (rotate it by 180°), the normal relationship between left-right head rotation and relative visual scene motion is reversed. For example, head rotation to the right is accompanied by relative scene motion to the right; the seen world is no longer perceived as stationary (4). Spatial orientation is severely impaired. However, after an extended period of visual reversal (days to weeks), the seen world appears more stable (4), and subjective visual "normalcy" and coordinated movement are gradually restored (5). Active movement by the subject is thought to play a vital role in the adaptation process (6). The slow phase component of the horizontal vestibulo-ocular reflex (VOR), which contributes to perceptual stabilization under normal vision, reverses after a week or two of visual reversal (7). The neural pathways believed to mediate adaptive changes in the VOR have recently been explored in animals (8). One might also expect that the neural interpretation of visual self-rotation cues would reverse and be manifest perceptually in a reversal of the CV phenomenon. We have now demonstrated such a reversal, accompanied by only a modest reduction in vestibulo-ocular reflex gain, in 9 of 12 subjects within a brief (1- to 3-hour) period of exposure. Reversed CV could be demonstrated only when the moving stripe display size was limited to the field of view conditioned by exposure.

Two experiments, which differed somewhat in procedural details, were

conducted with 12 adult volunteers with no overt oculomotor or vestibular disorders. As symptoms of motion sickness often occur under vision reversal, drugs (scopolamine, 0.5 mg; or scopolamine, 0.4 mg with Dexedrine, 5.0 mg) were orally administered before the experiment. In both experiments, left-right vision reversal was achieved using prism goggles, which permitted a binocular field of vision subtending approximately 45° horizontally and 28° vertically (9). (Horizontal dimensions will always be presented first.)

In both experiments, CV was tested before and immediately after a period of exposure to reversed vision (preliminary and final tests). In experiment 2, CV was also tested at intervals during the exposure period. Subjects were seated in the closed, motionless cabin of a flight simulator (Link GAT-1). Vertical light and dark stripes of equal width (6.4°) moving left or right at 8° per second were back-projected onto the translucent front window, about 70 cm from the subject. During testing without the goggles before and after exposure, the shape of the moving display could be varied through the use of appropriate masks applied to the window, whereas in tests made during exposure, the shape corresponded to the field of view of the goggles. Subjects were asked to verbally report the onset and disappearance of any CV. Because the goggles transposed the visual location of the hands, subjects were asked to report their perceived direction of self-motion with respect to the direction of seen stripe motion, with respect to their left or right eyes, or both. Motion reports made according to these two different methods were always consistent.

The gain and phase of the horizontal VOR were tested in the dark before and after exposure through the use of sinusoidal simulator angular motion (0.2 Hz, 30° per second peak velocity, 6 to 8 cycles). Eye movement was measured in the dark by conventional d-c electro-oculography. Subjects performed mental arithmetic tasks to maintain alertness.

During exposure, when not participating in the brief CV tests, our subjects explored their reversed visual environment