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Performance

Introductory article

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Human performance is a field of research focusing on the study of elementary sensorimotor skills in well-defined task environments that require fast and accurate responses. Among other things, processes related to the initiation and interruption of responses in single and dual tasks, such as motor planning, response selection, response execution, and response inhibition are investigated.

INTRODUCTION

Human performance is a field of research in which elementary sensorimotor skills are studied. These building blocks of human behavior involve sequences of an external stimulus and an observable action in response to the stimulus, with a well-defined relation between stimulus and action. That is, people are instructed to emit a specified response once a certain stimulus appears. Additionally, they are put under pressure to respond rapidly and without errors. Typically, the experimenter measures both the speed and the accuracy of responses in different conditions. As these aspects of human behavior are relevant to industrial productivity and safety, research on human performance was initially closely related to applied questions such as the design of dashboards or workplaces.

STARTING AND STOPPING ACTIONS

Indicators of Response Preparation

There are many indicators that bear witness to cognitive processes related to a response before that response is visible to an observer. If the electrical activity of the brain is measured by electrodes attached to the scalp, it can be observed that the brain potential on the side of the head opposite to where a response is about to be executed becomes more negative than the potential on the same side. For instance, if a person is instructed to press a left key, the electroencephalogram shows that the brain potential on the right side is more negative than that on the left. This phenomenon is called 'lateralized readiness potential' (LRP) because it has been shown to be involved in response preparation. Notably, the LRP may occur even slightly before the person is consciously aware of intending to execute the action. Thus, physiological events in the brain (at least occasionally) precede our awareness of action plans. At a peripheral level, the electromyographic activity at the muscle rises about 50 ms before the muscle actually moves. Finally, the observable response is emitted. The time between stimulus onset and onset of the associated response is the reaction time (RT). It is common practice to draw conclusions about motor preparation or planning from the analysis of psychophysiological indicators and RT. Any one of these indicators is incomplete as it never captures all aspects of motor planning; however, as a sum, they may be used to derive models of cognitive motor planning. By far the most widely used of these indicators of human performance is the RT. Different types of reaction time may be distinguished. If there is only one possible stimulus and only a single response associated with it, the observed latencies are simple RTs. If there is more than one stimulus, and several associated responses, choice RTs are measured. Typically, choice RTs are longer than simple RTs.

Simple Reaction Time

Simple RT is usually of the order of 200 ms, but the exact time depends on a number of factors. On the stimulus side, it has been shown that the intensity of the signal affects simple RT. The higher the intensity of the stimulus, the faster the response. For instance, bright targets yield faster RTs than dim targets, and loud sounds yield faster RTs than soft ones. Also, stable characteristics of the person affect simple RTs. Simple responses of young and alert persons are faster than those of older and less alert persons. The degree of preparation is a further determinant of simple RT. Generally, increasing the level of preparation by presenting a warning signal speeds up simple RTs. However, the ability to maintain a high degree of preparation is limited. When the time between the warning signal and the stimulus is long, the beneficial effects of the warning signal disappear. Further, simple RT increases with uncertainty about the time when the stimulus will appear. Responses are faster if the person is sure about when the signal will occur than when the time of signal presentation is uncertain. Finally, simple RT depends on the effector that is executing the response. The larger the mass of the effector, the longer the response latency. For instance, lifting the finger is faster than flexing the elbow, and flexing the elbow is faster than flexing the shoulder. The reason for these differences may be electromechanical factors related to the size of the effectors, not the programming of the response: the time between stimulus presentation and the first electromyographic activity at the peripheral muscles is the same for all effectors, such that the central processes related to motor programming do not differ. Only the time between the first electrical activity at the muscle and the muscle movement differs as a function of effector.

Choice Reaction Time

Choice RT differs from simple RT in that a response has to be selected from an array of alternative responses (two at the minimum). A large variety of responses is available. For instance, the experimenter may ask for key presses on a keyboard with four keys arranged in a square, or for joystick movements to the left, right, up and down, or for verbal responses such as ‘yes’ and ‘no’. In choice tasks, the stimuli are mapped onto responses: that is, the stimulus determines which response has to be executed. Usually, the mapping of stimuli onto response is conveyed by verbal instruction. For instance, the digit 1 appearing on a computer screen may require a joystick movement to the left, and the digit 2 may require a joystick movement to the right. Choice reaction time is longer than simple reaction time because the response in a choice task cannot be as well prepared as the response in a simple task.

The number of response alternatives in choice tasks has been shown to affect directly choice reaction time. Choice reaction time increases with the number of response alternatives: when people are asked to press one of n keys laid horizontally out in front of them whenever one of n lights located directly above the keys is turned on, RTs increase with n. The relation between n and choice reaction time follows a nonlinear function that has become known as the Hick–Hyman law. It states that choice reaction time increases linearly with the logarithm to the base 2 of the number of response alternatives (n). With an increase of 1 in the logarithm, the response time increases by about 150 ms. (*See* **Action**)

Stimulus–Response Compatibility

It is commonly observed that the speed of a choice response depends on how responses are mapped onto stimuli. Generally, the more natural or intuitive the mapping, the faster the responses. For instance, responses are fast when a left stimulus has to be responded by a left response and a right stimulus by a right response, but slow when a left stimulus has to be responded by a right response and a right stimulus by a left response. The former mapping is referred to as a compatible mapping. Stimulus–response compatibility may lead to violations of the Hick–Hyman law. When the assignment of responses to stimuli is extremely compatible, for instance when the tactile stimulation of a finger has to be responded to by depressing the stimulated finger, no increase of choice RT with the number of alternatives is noted. (*See* **Action**)

Sequences of Responses

The previous sections were concerned with a single action as a response to a stimulus. In this section, sequences of actions that follow an external stimulus are discussed. *A priori*, two ways of handling motor programming of a sequence of movements may be distinguished. First, the programming may be done in advance, and the program is only executed once the response is initiated. In this case, a motor output buffer is needed that retains the sequence of motor commands. Assuming that motor commands have to be loaded into the buffer one after the other, the time to load the buffer with commands increases with the required number of commands. Second, movement programming may be restricted to one movement at a time, such that in a sequence of actions, programming and execution alternate. In this case, no effect of number of movements on the reaction time of the first response should occur. The empirical research suggests that the truth lies in between these extreme views. In support of prior programming, it was observed that the reaction time to initiate a movement sequence increases with the number of movements that have to be executed. For instance, lifting a finger is faster than grasping a tennis ball, which in turn is faster than grasping the tennis ball twice. Note that the question is how fast these movement sequences are initiated – that is, how fast a home key is released before the sequence is executed – not how long the sequence lasts. A similar slowing with increasing number of movements has been observed with sequences of key presses, spoken syllables and written letters. In support of the ongoing programming view, the reaction time of individual movements in a sequence varies as a function of their serial position. At some serial positions, reprogramming of the upcoming movements is necessary, which slows down the response. Thus, sequences of movements cannot be fully pre-programmed, suggesting that the motor output buffer has a limited capacity.

Stopping an Action

Many situations require people to stop their ongoing actions. The successful operation of a stop process may be just as important for survival as the ability to initiate an action quickly. In stop-signal experiments, participants are given a primary task to perform and a stop signal is intermittently presented telling them not to respond on that trial. One may think of the processes related to the stop signal and those related to the primary task as independent sets of processes that are contestants in a race: if the primary task process finishes before the stop-signal process, the response is executed, but if the stop-signal process finishes before the primary task process, the response is inhibited. Studies using the stop-signal paradigm revealed that the stopping of actions does not differ substantially between individuals, strategies or tasks. The latency of inhibition is of the order of 200 ms. Also, the stop-signal paradigm allows for the evaluation of ballistic processes involved in action execution. Ballistic processes cannot be inhibited once they begin; rather, they must run to completion. Little evidence for ballistic processes was obtained. For instance, one might assume that during typing, whole words are programmed, and the typing of the word sequence is ballistic. This is hardly the case. When typists were given an auditory stop signal during typing, they were able to stop typing after a single keystroke, regardless of word boundary (the only notable exception being 'the').

ERRORS OF PERFORMANCE

Errors are usually not independent of the speed with which an action is performed. When errors and reaction time both follow the same pattern across conditions, it might be concluded that performance was affected by the experimental variation. For instance, in an easy condition, fast responses and few errors may be observed, whereas in a difficult condition, slow responses and many errors occur. In this case, one might attribute differences in performance to the difficulty of the conditions. However, if errors and reaction time do not follow the same pattern, strategic decisions of the participant, not the properties of the experimental conditions, might account for the observed performance. If people opt for a daring response strategy, their responses are fast, but they make many errors. Alternatively, they may choose a cautious response strategy, implying that their responses are slow and few errors occur. In other words, participants may trade off speed and accuracy.

At least two types of errors may be distinguished: choice errors and serial order errors. If people select the wrong response from an array of possible responses, this is called a choice error. Serial order errors occur when a correct response is selected, but it is emitted at the wrong position. The exchange of speech sounds such as 'The queer old dean' instead of 'The dear old queen' show that we sometimes confuse the serial order of initial consonants. Also, these errors tell us that we store motor programs for a series of actions. In sum, errors of performance are another measure to characterize human performance in addition to reaction times.

COMBINING BEHAVIORS

Coarticulation

In a stream of actions, it is often efficient not to wait for one action to end before another is initiated.

Coarticulation refers to simultaneous motion of effectors that makes a series of movements more efficient. It denotes that an upcoming action is prepared while another action is being performed. Such a strategy reduces latency of actions, and it leads to the combination of behaviors that are adjacent in time. The term 'coarticulation' was coined with respect to speech production, but the phenomenon encompasses other types of movements as well. For instance, finger movements during typing show that the fingers are not at rest until the previous keystrokes have been finished; rather, the hands move to their target positions ahead of time, allowing for fast typing rates. (*See* **Speech Production**)

Bimanual Rhythmical Movements

In the case of coarticulation, the simultaneous motion of two effectors is a by-product of efficient motor performance. However, it is also common to intentionally perform two movements at the same time. In particular, the production of rhythmical patterns involves simultaneous bimanual movements. However, research shows that our ability to perform two independent rhythmical movements with two effectors is very limited. A famous example may illustrate this point. The index fingers are flexed or extended resulting in a movement that resembles tapping (e.g. on a table top). Two basic relations between the movement of the two index fingers may be distinguished: left and right index fingers are flexed and extended simultaneously, which is referred to as in-phase pattern. In the anti-phase pattern, one index finger flexes as the other extends. When in-phase and anti-phase movement patterns are performed at a moderate speed, and the speed is subsequently increased, a striking difference emerges: whereas the in-phase pattern is stable across different movement speeds, the anti-phase pattern breaks down at fast speeds and a switch into the in-phase pattern occurs because it is easier in terms of the emerging perceptual or motor pattern. Thus, performance in tasks that involve continuous action of two effectors is severely limited.

DOING MORE THAN ONE THING AT ONCE

Dual Task Performance

In everyday life it is common to see people perform two different activities at the same time. Driving a car does not prevent people from having a conversation, and eating potato crisps does not keep them from watching television. Usually people do not experience any difficulty in concurrently carrying out two tasks, unless the tasks are intellectually challenging or physically impossible. Contrary to this belief, laboratory studies show that performing even simple tasks concurrently causes interference between the two tasks – that is, one of the tasks is performed less efficiently in terms of response time or proportion of errors.

The Psychological Refractory Period

In one important experimental design used to investigate dual task performance, observers are presented with two stimuli in succession, S1 and S2. The stimuli may be auditory, visual or even tactile, and they do not have to be presented within the same modality (e.g. an auditory S1 may be combined with a visual S2). The stimuli S1 and S2 are temporally separated by a variable stimulus onset asynchrony (SOA). Typically, the SOA varies

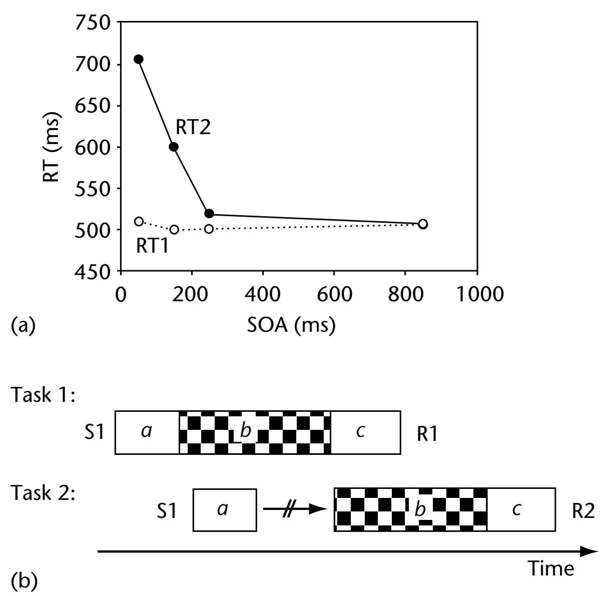

Figure 1. (a) The psychological refractory period effect. The reaction time for the first task (RT1) is unaffected by the stimulus onset asynchrony (SOA), whereas the reaction time in the second task (RT2) is longer at shorter SOAs. (b) The central bottleneck model of dual task performance. Cognitive processes *a*, *b* and *c* intervene between stimulus presentation S and response execution R, in two tasks. Process *b* (checkerboard region) is a bottleneck because it cannot begin in task 2 until the corresponding part of task 1 is complete. Process *b* has been associated with response selection.

between 0 ms and 1000 ms. Before the experiment starts, the participant is instructed to respond to S1 with a response R1, and to S2 with a response R2 (Figure 1). By far the most common responses are key presses because they can be easily recorded on a keyboard. Other responses include vocal responses, eye movements or foot movements. Again, R1 and R2 do not have to originate from the same effector (e.g. a manual R1 may be combined with a vocal R2). A large number of mappings between stimulus and response are possible and a fair percentage of them have already been tested. However, the main finding is robust across a large number of possible combinations of stimuli and responses: the time elapsing between the onset of S1 and the execution of R1 (RT1) varies little as a function of SOA between S1 and S2. In contrast, the time between onset of S2 and execution of R2 (RT2) increases dramatically when the SOA between S1 and S2 is made short. This finding is referred to as the psychological refractory period (PRP) effect. The PRP effect is the slowing of performance in one (or sometimes both) of two speeded tasks when the two tasks are performed at approximately the same time.

Other Dual Task Situations

Contrary to our everyday experience, the PRP effect shows that performance in two apparently easy tasks is slowed if they are performed at the same time. However, there are also dual task situations in which no interference between the two tasks occurs. When participants are engaged in a task without response uncertainty, such as repetitive finger-tapping or saying 'the' repetitively, there is almost no slowing of concurrent speeded responses in a different modality or of mental operations such as counting. Also, when there is no speed pressure on a perceptual judgment, it does not suffer from a speeded response in another modality. For instance, unspeeded visual identification of a letter is not affected by the approximately simultaneous response to an acoustic signal. Taken together, these findings suggest that the important distinction between dual task situations that show indications of interference and those that do not is whether both tasks or only one task requires a speeded response. Generally, whenever a rapid decision about a response has to be made in two approximately simultaneous tasks, interference results; otherwise, dual task interference is less likely and may be attributable to factors that are unrelated to the execution of the two tasks.

Models of Dual Task Performance

A widely accepted account of dual task performance, and in particular the PRP effect, is based on the assumption of a central bottleneck. A mental process *b* is considered a central bottleneck if (1) *b* is necessary for the completion of both tasks involved in a dual task situation, and (2) *b* may only be used by one task at a time. In other words, when a task (T1) lays claim on *b*, *b* cannot be used by another task (T2). Rather, T2 has to wait for *b* to be released from T1. Only after *b* has been released from T1 can T2 be completed. A central processing bottleneck would explain the PRP effect in the following way: when S1 is presented, the execution of the first task, T1, is initiated. Because S2 is presented after S1, execution of T2 is initiated after T1. Therefore, T1 claims *b* before T2 tries to. Consequently, with short intervals between S1 and S2, T1 may still occupy *b* when T2 is ready to use *b*. As a result, responses to S2 are delayed. With long intervals between S1 and S2, responses to S2 are faster because T1 has already released *b*, such that T2 has free access to it.

Considerable debate has focused on the nature of the central bottleneck. During the execution of a task that requires a particular response when a particular stimulus is presented, different processing stages may be identified: perceptual identification of the stimulus, selection of the correct response, and execution of the response. The central bottleneck may be located at any of these stages. Over the years, evidence has accumulated that the central bottleneck is located at the stage of response selection – that is, at the stage at which we decide whether to press the left or the right key, or whether to say 'a' or 'b' in response to a given stimulus.

The hypothesis of a central bottleneck in response selection has been criticized, on the grounds that the instructions in experiments on the PRP effect gave performance in T1 priority over performance in T2. That is, participants were asked to emit R1 before R2, possibly forcing them to use a bottleneck mechanism to postpone information processing for T2, so that responses to S2 did not occur before those to S1. Alternatives to the central bottleneck approach assume that the scheduling of processes in the PRP paradigm is under strategic control. That is, participants voluntarily decide to complete stimulus identification and response selection for T1 before tackling T2 because of the higher priority of T1, and not because of a structural bottleneck that forces them to do so. If participants had been given different instructions, they might just as well have scheduled response selection for T1 and T2 to occur at the same time (in violation of the second condition for a central bottleneck).

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Performance and Competence

Introductory article

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There is an important distinction between knowledge of the general principles of grammar (competence) and the way that knowledge is applied in actual language production or comprehension (performance).

Knowing the rules of addition is one thing. Actually adding a column of numbers is another. Likewise, knowing the rules of grammar is one thing. Actually using that knowledge to assign a structure and interpretation to a sentence is quite another. A theory of a native speaker's implicit knowledge of language is what is known as a 'grammar' or, equivalently, a theory of language competence. A theory of how that knowledge is applied to produce sentences, or to comprehend sentences, is a theory of language performance.

If one were to collapse the theory of competence and the theory of performance, a variety of problems would emerge. First, one would need to choose: should the theory characterize language production, mapping from an intended 'message' to a set of motor instructions, or should it characterize language comprehension, mapping from a perceptual input to an intended meaning? Given a theory of language competence, the well-formedness rule of grammar (the subject precedes the verb in English, the object follows the verb, proper names aren't preceded by determiners, e.g. **the Mary*) can be stated once and for all, even though this may be used for purposes of speaking, writing, listening, or reading.

Further, the theory of grammar can abstract away from issues concerning step-by-step processing in real time. The subject of a sentence must precede the verb independent of the moment-by-moment processing operations required to utter an actual sentence token or to understand one. To return to our addition example, imagine that the rules of addition were stated only in a theory of mathematical performance. In this case, someone who was capable of adding a column of numbers from top to bottom might be unable to add from bottom to top, or in groups with the even numbers added first and the odd numbers later. The step-by-step performance mechanisms would be inextricably bound up with the characterization of the mathematical principles themselves.

The grammar of English or any other natural language will define the well-formed sentences of the language (syntax), how they are pronounced (phonology), and what they mean (semantics). To account for actual language behavior, it must be determined what computation is performed at each step of processing, what information is consulted, what options are pursued at choice points, and the like. Without a detailed theory of language performance, it would be difficult to explain why some sentences are 'unacceptable' even though they are grammatical. Consider the sentences in (1):