Attention as a determinant of task performance: From basics to applications

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Abstract Attention is the ability to extract task-relevant information and reject irrelevant information in order to avoid excessive information processing in the nervous system, and influences task performance in daily life including physical and sporting activities. Basic attentional phenomena at the behavioral and neural levels have recently been employed as measures of attentional functions to examine the effects of exercise training and motor learning in the real world. However, these basic phenomena have been demonstrated in strictly manipulated laboratory experiments; therefore, it currently remains unclear whether they may be applied to the examination of attentional functions in real-world conditions. We herein briefly review basic attentional theories derived from a number of dual-task experiments and discuss their applicability to a more realistic world.

Keywords : attention, dual task, learning, resources, bottleneck

Introduction

Attention is the critical ability of humans to achieve goals in today's busy world. The human brain is bombarded with millions of stimuli from both external and internal environments. If all the information involved in these stimuli had to be fully processed, the brain would become overloaded, resulting in catastrophe. Therefore, the brain needs to select and exclude information based on certain criteria in order to avoid excessive information processing. Attention functions as an essential mechanism to select task-relevant information and exclude irrelevant information based on clues such as stimulus features. Thus, attention is one of the central research topics in cognitive science, psychology, neuroscience, and engineering.

However, since attention is a mental process or invisible phenomenon, it currently remains unclear whether it may be employed as a target in research. We herein present some intuitive examples showing that the concept of attention is reasonable as scientific matter. One of these examples is inattention blindness, which was demonstrated in a series of experiments conducted by Mack and Rock in the early 1990s¹⁾ and under real-world conditions by Simons and Chabris. Mack and Rock showed that individuals often failed to notice a fully visible, but unexpected object presented on a computer display when they were engaged in another task or focused on an object on the same display. This phenomenon is called inattention blindness. Sustained inattention blindness occurs even when the unexpected object is fully visible under real-

world conditions²⁾. Subjects were asked to watch a short movie and count the number of passes of a basketball by players wearing white shirts and ignore those made by players wearing black. Approximately 50% of subjects failed to notice the person in a gorilla suit entering the display, stop and face the camera, thump its chest on the center of the display, and then walk away. Inattention blindness makes individuals intuitively feel "I actually looked at the display to do the task, but missed such a noticeable object! I must have directed my attention to another object on this display". Thus, the most common explanation of inattention blindness is that attention is focused elsewhere on a demanding task on the same display. Thus, this phenomenon suggests the existence of attention in reality despite its invisibility, as well as the importance of attention in visual perception. Other examples such as spatial neglect and extinction have been reported in patients with brain lesions or disease. These patients behave as if they do not have an attentional system; their behavioral and psychological symptoms are explained by a lack of an attentional system. Furthermore, recent findings in neuroscience research indicate that attention is no longer a hypothesis. It is a realistic concept with a neural basis. These examples suggest the existence of attention in the mind or brain; however, it is still invisible. Approaches to examine this invisible phenomenon have not yet been established. One of the most effective ways to investigate attention is to raise and examine various objective phenomena that are likely to be associated with attention e.g., attentional changes in reaction times, task accuracy, and brain activity in an attention task or attention-related alterations in perceptions, cognition, and actions in patients with the specific diseases described above.

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Scientific importance of research on attention

The study of attention is very important not only theoretically, but also as an applied science³⁾. The theoretical importance of attention is considered in two ways. The study of attention is attracting increasing interest because it is one of the major limits of a human as an information processing device. Specific research questions are, for example, how many tasks may be simultaneously performed, how widely and rapidly attention may be deployed and switched across the visual field, across sensory modalities, and across different tasks, and how these phenomena may be explained using an integrated model. Attention is also closely associated with a number of mental phenomena, such as simple perception, complex cognition, working memory, learning, and decision making. Therefore, the mechanisms underlying these mental phenomena may not be elucidated in detail without clarifying the role of attention. The applied importance of attention is also considered in several manners. The mental phenomena described above are scaled up for real-world conditions such as being an eyewitness, motor skill training, item selection, and display design. Several difficulties are associated with scaling the basic theories of attention up to real-world conditions; however, this may be successfully achieved, as discussed later. Regarding brain pathology, when the attention systems of the brain are damaged by diseases or trauma, the impact on individuals and society may be significant; therefore, a clearer understanding of the neural mechanisms underlying attention is one of the central goals in neuroscience⁴⁾. These diseases and trauma include spatial neglect, extinction, developmental disorders, Balint's syndrome, dementia, Alzheimer's disease, schizophrenia, and Parkinson's disease.

The importance of the study of attention for physical fitness and sports science is also considered in various ways. Attention plays a general role in controlling elemental and coordinated sensori-motor skills in various sporting activities. Furthermore, it has a crucial effect on the automatization of sensori-motor processing in the course of learning. Therefore, knowledge of what and how attention needs to be directed in order to improve a skill provides important implications for the teaching skills of instructors and coaches. In addition, attentional phenomena at the behavioral and neural levels provide a unique tool for assessing the effects of sensori-motor learning, exercise training, and rehabilitation. Attentional phenomena may also be valuable for assessing the pathology and pathophysiology of several deficits in attentional functions as well as the effects of exercise because previous studies reported the benefits of exercise on these diseases.

In this review, we summarize basic research and theories of attention, particularly those derived from dual-task experiments, and consider their application. Classical attention theories remain valid, with some being applicable to real-world conditions. Since there are numerous theo-

ries for attention, we herein introduce some of the main and important ones. We also provide a brief overview of the current status of the study of attention in brain research.

Dual- or multi-task studies

Daily life often requires the performance of two or more tasks simultaneously. This type of dual-tasking or multitasking also occurs when individuals perform two or more short tasks in rapid succession or switch from one task to another. A good example is driving. A learner driver may encounter difficulties performing multiple tasks, e.g., monitoring the road through the windshield, turning the steering wheel, manipulating the gas pedal and brake, and looking at the speedometer⁵⁾. This is similar to learning a sport, such as playing basketball. The combination of moving, dribbling a basketball, monitoring teammates, opponents, and the location of a hoop, thinking of passing the ball to a teammate, and driving in or taking a jumping shot may be overwhelming. In the early stages of learning, these tasks are consciously executed. The need for conscious effort decreases with practice. A skilled basketball player or driver may perform multiple sensori-motor tasks simultaneously and smoothly as if it is a single task. Therefore, dual-task proficiency affects sport performance. The effects of practice have been investigated in dual- or multi-task experiments, and resource and single-channel theories have been proposed to explain dual-task performance.

Automatic and controlled processing

A classical, but very important series of single-task experiments, in terms of attention, performance, and related learning, need to be introduced before moving to resource and single-channel theories, namely, the theory of controlled and automatic processing proposed by Shiffrin and Schneider (1977). In a multiple-frame visual search task, they found that a visual search was independent of the number of items in the memory set and display under consistent mapping (CM) conditions (in which the target and distractors are mapped consistently), and this sort of finding reflected automatic processing in that the search was performed in parallel⁶⁾. In contrast, under varied mapping (VM) conditions, in which the target and distractor set changed from trial to trial, they found increased reaction times to the target as well as the number of distractors in the display. These results are considered to be indicative of controlled processing. Shiffrin and Schneider found that the processing of items divided by novel distinction for consistent mapping (CM) changed to automatic processing after more than 2100 trials, and also showed that just after reversing the mapping (i.e., changing the rule), performance worsened with increased reaction times and was limited by both the memory set size and number of

distractors⁷⁾. Subjects needed 2400 trials to improve their performance. The latter finding shows that humans have difficulty or require a substantial amount of time to unlearn an automatic response to targets or overcome some habitual inhibition to distractors learned through extensive training. In contrast, for varied mapping (VM), performance may be easily changed by instructions, which suggests that another type of processing can be quickly adapted by conscious intention. In a similar type of visual search task, letters were detected in parallel with other attention tasks for consistent mapping⁸⁾, suggesting the development of automatic processing. In contrast, performance in a similar letter categorization task, but with a set of target letters varying trial-by-trial (i.e., for varied mapping) was improved less by extensive training, and the decrease in dual-task performance was not eliminated. Other studies have also reported that the semantic target category and non-verbal information enable this type of automaticity, which produces perfect time sharing^{9,10)}. These studies mainly examined automaticity in the perceptual domain, whereas others reported automaticity in the cognitive¹¹⁾ and motor domains^{12,13)}.

Resource vs. single-channel theory of attention and its integration

Dual-task performance is explained by the limited capacity or resource theory. The first capacity model was suggested by Kahneman (1973), and is called effort¹⁴⁾. In this model, the amount of mental activity needed depends on the difficulty of a given task, even if the task is automatic or controlled processing. A prerequisite is that humans have a limited capacity for information processing. When humans perform multiple tasks concurrently, the tasks are not achieved well if the entire amount of processing required for each task exceeds the given limited capacity, and this is called “effort”. Effort is regarded as a type of mental energy or resource. Therefore, the basis of this model is the hypothesis of a limited capacity and allocation system. The concept of resources was subsequently introduced instead of effort¹⁵⁾. Resources include memory capacity, the transmission network, and effort, which are required to perform cognitive tasks. In this model, two types of processing were considered. In resource-limited processing, task performance improves in proportion to the amount of resources allocated to the task. In data-limited processing, performance is independent of the amount of resources allocated to the task. The development of automatic processing corresponds to the transition from resource-limited to data-limited processing.

Another proposal to explain dual-task performance is the single-channel or bottleneck theory. The single-channel model is based on the assumption that parallel processing is impossible for certain mental operations. In this model some operations simply require a single dedicated mechanism over a period of time. When two

tasks require the same mechanism at the same time, a bottleneck results, and one or both tasks will be delayed or otherwise impaired. Evidence for the single-channel theory has been obtained in studies on the psychological refractory period (PRP)¹⁶⁻²⁰⁾. In a typical PRP experiment, subjects are instructed to respond to two stimuli presented in rapid succession. Reaction times to the second stimulus are longer when the second stimulus is presented after a very short stimulus onset asynchrony (SOA) than when presented after a longer SOA. This provides evidence for a bottleneck, in which two different tasks cannot be processed at once and processing of the second task must be suspended until processing of the first task is completed. Previous studies localized the bottleneck in the stage of response selection¹⁷⁾, post-selection¹⁹⁾, both²¹⁾, and response activation²²⁾.

Thus, the single-channel model has the all-or-none feature (open or closed) and consists of only serial processing, whereas the resource model has a continuously allocatable feature and allows parallel processing. This basic difference in features has resulted in several debates over 2 decades. In contrast, attempts have been made to integrate these theories. Evidence to support the single bottleneck model is consistent with a simple resource model²³⁾. The resource model subsumes the single-bottleneck model, in which a serial bottleneck is regarded as a special type of resource. Tombu and Jolicoeur suggested a central capacity model and proposed that a central bottleneck model represents a special capacity model in which all capacity is allocated to one task when two tasks require central processing^{24,25)}. The central capacity model is not only one of the alternative accounts for the PRP effect, but may also be regarded as the integration of the single-channel and resource models. In addition to their central capacity model and Pashler’s structural bottleneck model, Tombu and Jolicoeur proposed the “strategic bottleneck model” suggested by Meyer and Kieras¹⁹⁾ as another explanation for the PRP effect; but also indicated that this is still a bottleneck model. Wickens and McCarley (2008) reported that the mediating concept of effort or resource demands may create single-channel theory behavior when effort is high, automatic behavior when effort is low, and something in between when effort demands are moderate. There are still a number of debates that make it difficult to differentiate between the single-channel and central capacity models of the PRP effect and other types of dual-task interference; however, these models may be more comprehensively integrated into a single theory of attention in the future.

Attention in cognitive neuroscience

Attention has been one of the central issues in neuroscience since the 1960s. Early studies investigated the neural mechanisms underlying attention using evoked- or event-related brain potentials (EPs or ERPs), which is the time-

and phase-locked brain activity associated with certain events. These basic studies demonstrated various types of attentional modulations of ERPs associated with a number of attentional phenomena, such as selective attention²⁶⁻²⁸⁾, resources²⁹⁻³¹⁾, and response selection³²⁾. For example, previous studies showed that the amplitude of the P3 component was closely associated with the amount of resources allocated to a given task in dual-task experiments^{29-31,33)}. These studies also showed that dual-task practice usually results in earlier automatization of the stimulus evaluation process, and includes different processes from single-task practice^{5,34)}. Early studies described the attentional modulation of neuronal activities within individual sensory modalities, whereas recent studies demonstrated cross-modal links in attention^{31,35-39)} and the effects of motor preparation on attentional modulation⁴⁰⁻⁴⁶⁾. Furthermore, in this decade, various neural phenomena of attention have been identified using sophisticated recording and analysis methods such as functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG) as recording methods, and time-frequency, connectivity, and network analyses as analysis methods⁴⁷⁻⁵⁵⁾. Other stimulation methods including transcranial magnetic stimulation (TMS), direct/alternate current stimulation (tDCS/tACS)), and random noise stimulation (tRNS) and their combination with other methods are also valuable for examining the causal role of relevant brain regions in attentional processing and for artificially manipulating their activities and functions⁵⁶⁾. The current consensus is that attention is achieved by various modules and their communication in the large-scale brain network, such as alerting, orienting, and executive networks, dorsal and ventral networks, or resting and task networks⁵⁷⁻⁶²⁾.

Applicability of basic attention theories and findings

A substantial gap exists between the attention theories demonstrated in laboratory experiments and attention practice under real world conditions including daily life and sporting activities. For example, a large number of basic studies on attention repeatedly reported improvements in task performance with practice under various single- or dual-task conditions, which have been associated with resource or single-channel theories. In contrast, the findings of some applied studies on attention emphasized that the internal focus of attention has no or limited beneficial effects on motor learning, whereas the external focus of attention is beneficial⁶³⁾. Researchers have to fill these gaps between basic and applied fields of attention. Thus, a general question on attention in physical fitness and sports science is whether and how these basic theories of attention, derived from laboratory experiments, may be applied to more complex, real-world conditions. Wickens and McCarley (2008) suggest in their book “Applied attention theory” that several types of applications may be successfully achieved in light of psychology,

ergonomics, and neuroscience by reviewing a number of basic theories and studies on attention. For example, the automaticity theory may be applied to training attentional skills and the timeline modeling approach to workload prediction. The single-channel theory can also be applied to workload modeling and workload prediction, as well as real-world conditions such as smartphone use during driving, walking, and cycling. Several good examples prove the applicability of basic attention theories to real-world issues, e.g., the real-world version of inattention blindness²⁾, in which a short movie of basketball is used as an experimental stimulus. Physical and sporting activities involve many interesting and extreme examples for investigating the functionality of attention and adaptability of basic theories under real-world conditions. One potential strategy is to test attention theories under experimental conditions resembling or simulating the real world in laboratory experiments.

Another important question is whether measures of attention, such as changes in reaction times, task accuracy, and brain activity in certain attention tasks, may be applied as measures of the effects of exercise training performed in the real world. Most studies still use measures of attention from laboratory experiments, including changes in reaction times or various components of ERPs in Posner’s attention task or in a visual search task; however, it currently remains unclear whether measures in laboratory experiments are sufficient to manifest training effects. Although the best strategy to overcome this is to measure behavior and brain activity during the performance of sporting activities or training in order to assess training or practice effects, this strategy is associated with several methodological difficulties. Regarding brain activity, a number of non-invasive brain imaging methods have been developed as described earlier, but are not yet available in the real-world environment outside the laboratory. One possible method to achieve this may be EEG. Recent advances in technology have resulted in the development of portable multi-channel EEG devices for real-world application. Some techniques of artifact rejection and correction have enabled reliable brain, autonomic, muscular, behavioral, and biomechanical signals to be simultaneously recorded under real-world conditions outside the laboratory. This may allow researchers to elucidate the mechanisms and functions of attention in daily life and sporting activities, and compare them with basic theories of attention. Virtual reality techniques may also facilitate this type of research by comparing real-world and virtual reality conditions. In this regard, another important issue is the development of an effective system that presents stimuli with accurate timing depending on the participant’s status as well as the environmental status in complex real-world conditions in order to fully utilize the performance of EEG with excellent temporal resolution. These issues may be applicable to any study on a number of other perceptual, cognitive and motor func-

tions and are of interest for future research.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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