Theoretical Investigation on Disuse Atrophy Resulting from Computer Support for Cognitive Tasks

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Abstract. We propose a new concept, disuse atrophy in cognitive abilities, i.e., cognitive disuse atrophy. Generally, the term "disuse atrophy" has been used to describe physical atrophy, such as muscle wasting. We advance the idea that disuse atrophy appears not only as physical loss but also as a loss of cognitive abilities. To understand the mechanisms underlying cognitive disuse atrophy, we note the duality of cognitive activities such as performance- and learning-oriented activities when engaging in tasks. It is crucial to investigate the balancing of these two types of activities as the assistance dilemma in learning science. We explored principles for controlling this balance based on two theories: cognitive load theory and goal achievement theory. Cognitive load theory distinguishes three types of cognitive loads. This theory proposes to suppress the extraneous load to the minimum, while assigning adequate amounts of the germane load for learning-oriented activities into working memory, and still leave enough resources for the intrinsic load of performance-oriented activities. Goal achievement theory assumes principles from the viewpoint of goal setting. Specifically, orientation to a performance goal activates performance-oriented activities, and orientation to a learning goal causes learners to direct their efforts to learning-oriented activities.

Keywords: Disuse atrophy, Assistance dilemma, Cognitive load theory, Goal achievement theory.

1 Introduction

1.1 Automated Systems as a Third Generation of Tools

Humans have acquired overwhelming abilities by developing a variety of tools for cultivating and extending their controlled world. Knives and hammers are representative examples of tools that have been used since ancient times. These tools are used to support physical human activities such as cutting, hitting, and building and are regarded as the first generation of tools in the history of tool development.

By the end of the twentieth century, new type of tools, known as cognitive artifacts have emerged in our society [19]. Cognitive artifacts are regarded as

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the second generation of tools. These tools support human cognitive activities and are often called "systems" because of their functions. These systems are significantly different from traditional tools in their functionality, which is referred to as multiple, high-level editing, and interactive functionality. This difference cause discordance between users' intentions and actual processing conducted in a system [20][24].

Yet another new type of system has recently emerged, i.e., automated systems that perform autonomous activities such as automatic driving vehicles and automatic cleaning robots. These tools have unique natures that are different from traditional tools that support human physical and cognitive activities [22][25]. These automated systems can be seen as the third generation of tools.

In the use of traditional tools and systems, humans have the primary role of performing a task, and the system is secondary in support of the activity. Even when large roles are assigned to systems in performing a task, the relationship between systems and humans has been characterized as a collaboration in which mutual interaction is a key factor for determining total performance. But in the use of automated systems, the system becomes the main actor and the task of the human is to monitor the behavior of the system.

Information processing by automated systems that carry out tasks rather than humans is extremely complex. Hence, the inner processing of the system is usually packaged as a black box, which is impossible to be understood by the user. In second generation systems, there is a similar but less developed aspect, so users must construct mental models to understand and interact with these systems. However, in third generation systems, users often entrust the entire operation to the system without even minimal understanding of the workings of the system.

1.2 Cognitive Disuse Atrophy

Automated systems undertake tasks in a variety of fields and greatly enhance human abilities for working. However, the convenience emerging from the use of such systems has, in some cases, caused negative impacts on human society. A majority of people may be experiencing these issues in daily life, e.g., difficulty in memorizing maps due to daily usage of a car navigation system or difficulty remembering the accurate spelling of words because of using a word processor with spell checker software. Initially, Norman highlighted issues related to the use of automated systems. Human factor studies have reported that the continuous use of automated systems decreases users' manipulation abilities [25] and, more seriously, complacency on this front causes aircraft accidents [31].

This study proposes a new concept, cognitive ability disuse atrophy, i.e., a loss of cognitive ability due to a lack of use. We see this as a key issue underlying some human factor problems that emerge when people engage in cognitive tasks in collaboration with computers. This study is a theoretical investigation of this issue. The term "disuse atrophy" is generally used for physical body atrophy, such as muscle wasting. When muscles are no longer in use, they slowly weaken. This weakening, or atrophy, can also occur from continuous physical support that leads to a minimal use of the body. We advance the idea that disuse atrophy occurs not only in the physical body but also in cognitive ability.

1.3 Duality of Cognitive Activities

To understand the mechanisms underlying cognitive disuse atrophy, we begin with the duality of cognitive processing when engaging in a task. Generally, there are two objectives for performing a task. One ordinary objective is to perform and complete the task. However, there is another important objective, i.e., for performers to develop proficiency and knowledge by performing the task. Performance and mastery are the prime reasons to engage in a task. We contend that disuse atrophy emerges when the aspect of mastery is lost.

For example, consider car navigation systems. When a person searches for a route from a current location to a new destination, they usually try to remember a mental map, a configuration of the possible pathways, select candidate pathways related to the target route, and decide on the best route from multiple candidates while considering current traffic and construction. These cognitive information processing efforts develop mastery for remembering maps and acquiring the skills to search for a route. However, when we use a navigation system, we do not need to perform any such mental activities, because all of this type of processing is performed by the system. All the person has to do is enter the destination and press the confirmation button. From the viewpoint of performance that is all it takes to achieve the goal. But for remembering a map and becoming able to find a route with a printed map, such mental activities that lead to mastery are important. Because car navigation systems deprive users of making such efforts for mastery, they cause mental disuse atrophy.

2 The Assistance Dilemma

2.1 Performance- and Learning-Oriented Activities

Next, we investigated issues related to performance and mastery from the viewpoint of the duality of cognitive activities in learning. When students engage in learning through practice, they usually solve problems for exercise. Note that cognitive activities for solving problems are not necessarily equivalent to cognitive activities for learning. Consider a learning situation in which students learn procedural knowledge to solve mathematical problems. Students solve example problems by applying the procedural knowledge. To optimize the learning effects, students should examine the conditions under which the knowledge applies, relate the newly acquired knowledge to previously acquired knowledge while considering the relationship between the two knowledge sets, and finally, generalize the knowledge for application to a variety of problems. This paper defines the former cognitive activities related to problem solving as "performance-oriented activities" and the latter cognitive activities for learning as "learning oriented activities." Performance- and learning-oriented activities correspond to cognitive activity for performance and mastery as discussed previously. Both activities are required to maximize the effects of learning.

2.2 The Assistance Dilemma

The importance of balancing these two types of cognitive activities has been recognized as the assistance dilemma. Recent intelligent tutoring systems have highly interactive features. Such systems give participants a variety of feedback, such as verification, correct response, try again encouragement, error flagging, and elaboration messages. In this context, the assistance dilemma has been recognized. Koedinger and Aleven (2007) pointed out a crucial question: How should learning environments balance assistance giving and withholding to achieve optimal learning? [13] The problem is that high assistance sometimes provides successful scaffolding and improves learning; but at other times, it elicits superficial responses given without consideration. On the other hand, low assistance sometimes encourages students to make great efforts in learning, but other times it results in enormous errors and interferes with effective learning. To solve this dilemma, the levels of support in tutoring systems must be adaptively controlled.

Figure 1 illustrates the assistance dilemma. Consider a student who is solving problems for exercise while receiving assistance from a tutoring system. The horizontal axis represents the level of support, defined by the amount of help information. The level of support is at the minimum when the student solves the problems by themselves without system assistance. The level of support is at the maximum when the student is given a final solution directly. The latter is called a bottom out hint. The vertical axis shows the problem solving performance during the learning phase and the achievement level of learning that is measured after the learning phase. The former is usually evaluated by the solution time, the rate of incorrect answers, and the errors committed in solving problems while assistance is being given. The latter is evaluated by post-test scores when problems are solved by the students themselves without assistance.

Figure 1 shows that as the level of support increases, problem solving performance also increases constantly; but the post-test scores indicate that the learning effect reaches its peak at the optimum assistance level and begins to decrease from that point, meaning that over-assistance occurs in the left side of the graph.

The assistance dilemma occurs in the left side of the graph. The dilemma is caused by the duality of cognitive processing. Tutoring support activates performance-oriented activities and improves problem solving performance, but over support contradictorily inhibits learning- oriented activities, thus causing the assistance dilemma. Now we go back to the issue of disuse atrophy. Automated systems perform everything. Humans do not need to do anything. From the viewpoint of the assistance dilemma framework shown in Figure 1, we infer that support level almost reaches the maximum at the leftmost side of the graph resulting in the emergence of cognitive disuse atrophy.

2.3 Empirical Evidence of Dilemma

Miwa, et al. empirically confirmed the dilemma of the performance and learning curves depicted in Figure 1 using two experimental tasks [16]. One was the Tower

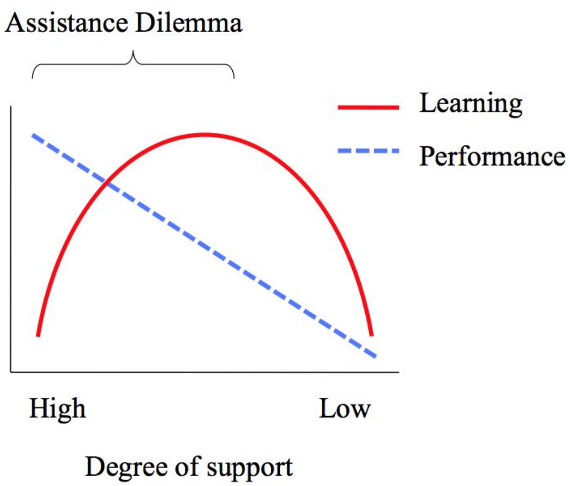

Fig. 1. The Assistance dilemma and performance and learning curves as a function of the levels of support

of Hanoi (TOH) puzzle, which is a representative experimental task widely used in problem-solving studies. The other was a natural deduction (ND) task. TOH is a simple task in which the problem space is systematically organized and is not very large. Problem solving is achieved by only one operator that corresponds to disk movement. The knowledge and strategies for the solution are represented by less than ten production rules, whereas ND is a more complex task in which problem space is much larger than that of TOH. To solve problems, since participants must acquire many kinds of inference rules and solution strategies, a complete model for solving ND problems consists of around a hundred production rules. The assistance dilemma was confirmed in both such relatively different types of tasks.

3 Cognitive Load Theory

The balance of performance- and learning-oriented activities is critical to solving the problem of cognitive disuse atrophy. How can we control the balance of the two activities? To answer this question, we examine two theories: cognitive load theory constructed in cognitive and instructional sciences and goal achievement theory developed mainly in educational psychology. Cognitive load theory (CLT) has provided informative perspectives for designing learning environments based on the constraints of cognitive architecture. In this study, we reinterpret the relative findings of CLT for balancing learning- and performance-oriented activities.

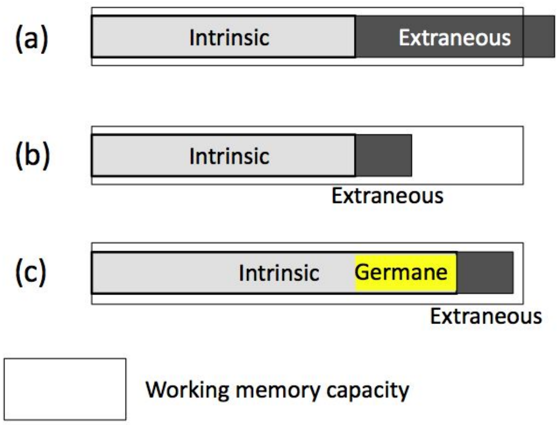

Fig. 2. Relation of intrinsic, extraneous, and germane loads

3.1 Three Types of Cognitive Loads

CLT distinguishes three types of cognitive loads: intrinsic, extraneous, and germane [27][29]. The intrinsic load is defined as the basic cognitive load required to perform a task. As the difficulty of the task increases and the degree of expertise of the performer decreases, the intrinsic load increases. The extraneous load is defined as wasted cognitive load that does not relate to learning activities, but emerges reluctantly. One reason that the extraneous load occurs is due to the inappropriateness of learning material designs. For example, when related information is not arranged properly, the extraneous load is increased by the efforts of doing irrelevant searches to gather the related information. The germane load is defined as the load used for learning, such as for constructing schemata activities.

Figure 2 illustrates the relationship among the three cognitive loads [29]. Figure 2 (a) illustrates the status in which the cognitive load exceeds the limits of the performer's working memory capacity due to the increase in the extraneous load. In this overloaded situation, learners make enormous errors, spend too much time performing the task, and occasionally, may not be able to perform the task. Figure 2 (b) shows cognitive loads that fall within a range where learners perform a task easily and show good results. CLT proposes that in such situations with memory capacity to spare, it is important to raise the germane load to activate learning activities, as illustrated in Figure 2 (c).

3.2 Controlling Cognitive Loads

It is assumed that the intrinsic load occurs to perform performance-oriented activities and the germane load increases to perform learning-oriented activities. CLT has revealed how these loads vary with changes in the degree of learning support.

Adequate support lets learners perform a task easily and suppresses the intrinsic load. When materials are properly designed, the emergence of the extraneous load is also minimized and the working memory has plenty of room to perform the task. This is advantageous to performance-oriented activities, as illustrated in Figure 2 (b). To activate learning-oriented activities, the germane load should be increased. To do so, learners are properly guided to engage in learning-oriented activities, increasing the germane load while the extraneous load is still minimized, as illustrated in Figure 2 (c).

3.3 List of Design Principles

A list of principles for designing learning materials and systems to minimize the extraneous load and increase the germane load has been developed by CLT [27].

- **The Goal-free effect**: Set up a situation in which learners search for various solutions. To let learners to do so, do not provide a specific goal that drives learners into searching for a single specific solution.
- **The Worked example effect**: Worked examples are used as an alternative to learning by problem solving [26][21]. Worked examples are defined as a solution example that includes steps to solve the problem, equations for solving the problem, and the final solution. Learners are guided to follow the process of experts' problem solving by tracing their steps in the worked examples. Learning by worked examples minimizes the learners' extraneous load and provides memory space for assigning the germane load.
- **Spirit attention effect**: When relevant information is presented in a fragmented way, the extraneous load increases in the search for mutual references. Suppress the extraneous load by arranging related information together, e.g., including explanatory text in a figure.
- **The Modality effect**: In information presentation, combine multiple modalities to suppress a split-attention effect. For example, use auditory guidance for presentation with text information.
- **Redundancy effect**: Irrelevant information is separately presented no to be noted by learners because if such information is referred, the extraneous load increases.
- **Variability effect**: Let learners investigate a single topic with multiple representations and under various contexts, activating their cognitive efforts for generalizing knowledge and encouraging schema creation.

4 Goal Achievement Theory

4.1 Performance Goal and Learning Goal

Another decisive factor that determines whether learners assign cognitive efforts to performance- or learning-oriented activities are the goals they set for engaging in the task. Goal achievement theory (GAT) has provided theoretical perspectives on the relationship between the goals that students set for themselves and their learning activities. It has also accumulated a vast amount of empirical findings.

In GAT, student goals are divided into learning goals and performance goals [4]. Learning goals motivate students to aim for developing their own abilities, but performance goals are motivated by a desire to seek higher social evaluation, rather than their own development. This implies that the former goal activates learning-oriented activities and the latter activates performance-oriented activities. Similar goals that may relate to both goals have been investigated from a variety of viewpoints in various contexts. Table 1 shows a summary of a set of families of performance and learning goals [30][17][18][12][15][2][14]. Extensive meta-analysis was conducted about the relationships of such goals, each of which is called by a different name, but some of which share common properties[11].

Table 1. Distribution of the numbers of participants who drew the reversed figure in Experiment 1

Learning	Performance	
Intrinsic	Extrinsic	Lepper, Corpus, & Iyengar, 2005 Vansteekiste, Lens, & Deci, 2006
Task-involved	Ego-involved	Nicholls, 1984 Nolen, 1988 Jagacinski & Nicholls, 1987
Task	Ability	Midgley, et al., 1998
Mastery	Performance	Ames & Archer, 1988

In the early stages of the study, GAT findings stressed the superiority of learning goals over performance goals. Specifically, Utman (1997) confirmed, through meta-analysis of preceding studies, that the priority of the learning goal is more significant when performers are adult and tasks are complex [28]. Through the history of investigation, the shift from performance goals to learning goals has been regarded as adaptive development through which learners become challenged and exhibit higher independence in performing a task [1]. Meanwhile, it has been confirmed that when learners set performance goals that do not challenge them to new missions, they give up in the face of difficult requirements even though they are relatively proactive when they receive high evaluation.

Insert Table 1 about here Table 1: Family of the learning and performance goals.

4.2 2 x 2 Framework

After 2000, an additional dimension, defined as approach and avoidance status, began to be considered in the distinction of learning and performance goals, proposing a 2 x 2 framework [5][23][10]. Approach status is the orientation toward reaching high scores. Avoidance status is the orientation toward evading getting low scores.

In this framework, the disadvantage of the performance goal becomes prominent in the avoidance status. Rather, the performance goal in the approach status is regarded as a desirable attitude for achieving high learning effects. In the past, it has usually been confirmed that performance goals motivate more superficial cognitive processing, while learning goals activate deeper processing. However, Elliot, et al. indicated that in the approach status, orientation to the performance goal is positively correlated with test scores, even though in the avoidance status, it is negatively correlated [6]. Harackiewicz, et al. indicated that based on their meta-analysis of empirical studies, performance goals in the approach status lead to positive impacts on the improvement of task performance [9].

4.3 Controlling Goals

Although GAT did not intend to provide methods on how to control goal setting, some of the studies consider this point. One set of studies indicated the possibility that, with instruction, students' goal orientation can be controlled [8][7]. These studies showed that when the point where knowledge and skills are developed through achieving a task is stressed, learners are motivated to set learning goals. When one student's performance is compared to another, students are motivated to set performance goals. Another set of studies, e.g., Ames (1992) and Church, et al. (2001), explored goal setting from the viewpoint of curriculum design in classroom settings in which practical principles were used to guide students to orient toward setting learning goals [1][3]. Research indicated the possibility that student goal setting may be manipulated by several factors, such as the nature of study requirements, how they were being evaluated, how responsibility was assigned, and voluntary attitudes of students.

In GAT, performance and learning goals are regarded as decisive factors for assigning learners' cognitive efforts to performance- and learning-oriented activities. The accordance and conflict aspects for both goals reveal central issues of balancing learning- and performance- oriented activities.

5 Toward a Solution for Cognitive Disuse Atrophy

This paper confirmed that the duality of cognitive activities underlies the emergence of cognitive disuse atrophy. Specifically, atrophy is caused when performance-oriented activities are assigned for performing a task without the learning-oriented activities. This insight reveals that the balance of the two types of cognitive activities is crucial to avoid cognitive disuse atrophy. Two theories, CLT and GAT, challenge this issue from different stand points. CLT is usually used to assess issues of design principles for constructing learning materials and environments. Consequently, the investigation of the relationship between the two cognitive activities is explored from the outside environment. To maximize learning effects by manipulating the two cognitive activities, the extraneous load must be suppressed to the minimum and an adequate amount of the germane load must be assigned for learning-oriented activities into working memory, while reserving enough resources for the intrinsic load needed for performance-oriented activities. There are various principles proposed for doing so. However, GAT originates partially from personality psychology. Therefore, GAT theory has provided findings for controlling the two types of cognitive activities from inside the performers. GAT establishes perspectives for understanding the two types of cognitive activities from the goal setting perspective. Specifically, orientation to performance goals activates performance-oriented activities, while orientation to learning goals motivates learners to direct their efforts to learning-oriented activities. This paper proposes a first step for solving cognitive disuse atrophy based on the two primary cognitive theories that have been established from both theoretical and empirical perspectives.

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