Interactive Processes between Mental and External Operations in Creative Activity: A Comparison of Experts' and Novices' Performance

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ABSTRACT
Prior studies of creativity, in the field of cognitive psychology, have mainly dealt with only the process of mentally thinking of ideas. We investigated, through a cognitive psychological experiment and its protocol analysis, experts' and novices' interactive process between the mental operation by which participants considered their ideas and the external operations by which they actually produced physical objects in creative activity. In our experiment, the participants were required to build a creative robot with LEGO Mindstorms. The experimental results showed that the experts could create work that fulfilled both high originality and practicality simultaneously. Moreover, the following four points were confirmed as characteristics of the experts' creative process: (1) the experts globally considered their initial ideas, (2) the experts reconstructed their ideas by considering comprehensively the relationship among the elements constructing their plans, (3) the experts reconstructed their ideas more actively, and (4) the experts were able to embody successfully their ideas by focusing on various aspects of important viewpoints.

Categories & Subject Descriptors: H.1.2
General Terms: Human Factors
Keywords: Cognitive processes, mental operation, external operation, expertise, protocol analysis

INTRODUCTION
Preceding Studies
In studies of creativity in the field of cognitive psychology, the cognitive process of human creative activities has been discussed to answer the question: "What kinds of mental mechanisms underlie creative activities?" A series of studies by Finke and his colleagues based on the creative cognition approach are well-known as representative studies. The objective of this approach is to understand the human creative process based on the theories and experimental methods that have been used in cognitive psychology. Finke et al. proposed a cognitive model on the human creative process, called the Geneplore model, based on their findings [4]. This model grasps the human creative process as an interactive process between the following two stages: (1) the generative phase where mental representations are generated, and (2) the exploratory phase where the representations are interpreted. We have also analyzed, based on this Geneplore model, the cognitive processes of the creative activities of participants designing playground equipment [6]. As a result, we have confirmed that the process of the participants' creative activities is promoted by the interaction between a cognitive stage (corresponding to the generative phase), where imaginary shapes of playground equipment are generated, and another stage (the exploratory phase) where the functions of the equipment and its ways of playing are interpreted. Moreover the collaboration of a pair of participants engaging in this task can promote this process of interaction, and produce more sophisticated equipment.

Objectives of the Present Study
The preceding studies, including our study, have mainly dealt with only the process of mentally thinking of ideas. However, in real situations, when people create physical objects, ideas in their initial stage are rarely embodied without reconstruction. Generally, ideas are going to be embodied after receiving various types of feedback from the transitional results of the production and repeatedly revising the initial plan.

Therefore, the creative process should be characterized as both the external (physical) operation that tries to embody ideas into the physical world and the internal (mental) operation that considers ideas of products in the mind. Both kinds of stages are clearly not independent but are interactive processes. We can confirm this point by analyzing the creative processes of some actual famous inventors. For instance, observing the creative process of the Wright brothers who invented the airplane, they reached final success by performing repeatedly wind tunnel tests and receiving feedback from the experimental data [1]. Additionally, analyzing the invention process of Bell and Edison, who invented the telephone, we again find, in their process of creation, that first only a part of their ideas was embodied, and gradually they created their invention through repeating the revision and reconstruction process [2] [5]. The above facts imply the importance of studies focusing on the interaction between the mental operation considering ideas and the external operation embodying the ideas. Therefore, in the
present study, we conducted an experiment where the creative activities of experts who produce physical objects using their technical knowledge and skills are investigated. We then identified the characteristics of the experts' creative activities compared to the novices' processes of producing their works. The purposes of this research are summarized as follows: (1) to clarify in which aspects the products produced by the experts are excellent; and (2) to establish why and how the experts can embody their ideas well.

METHOD
Material and Task
We utilized Mindstorms produced by LEGO Co., Ltd. as the experimental material. The characteristics of the creative activities using Mindstorms are as follows: (1) the parts for the production are determined, (2) the number of the parts is constrained, and (3) the cost of reconstruction of the production is relatively low (the participants can freely rebuild their objects as many times as they want).

Using Mindstorms as experimental material enables us to analyze the creative activities including the external operation of the participants, in addition to the mental operation considering the ideas, such as constructing a module from the parts, constructing a mechanism with the electric motors and gears, and constructing an algorithm that controls the object's behavior in the programming environment. The mission given to the participants was to produce a creative robot that can move using Mindstorms.

Participant
Expert
Three persons who won first or second place in one of the major robot contests using Mindstorms held in Japan participated in the experiment as experts.

Novice
Four graduate students who majored in cognitive science participated in the experiment as novices. All of them had experience using LEGO Blocks; however, none had experience using Mindstorms.

Procedure
Before the experiment, the participants were given an experimental instruction. In the instruction, basic information on Mindstorms, and fundamental knowledge and concrete examples of the parts and mechanisms, were presented. The instructive session lasted for about 30 minutes. The concrete contents of the instruction are as follows.

Basic information
• The types of parts and how to use the parts.
• How to program an algorithm for controlling the robot's behavior.
• How to download the program.

Fundamental knowledge on the parts and mechanisms
• The ways of strengthening the parts.
• The ways of transforming the velocity and strength of rotary motion.
• The ways of transforming the direction and angle of rotary motion.
• The ways of transforming rotary motion into reciprocating motion.

After receiving the above instruction, the participants were given a planning sheet on which both their ideas on a robot (before production) and their evaluation and analysis on the progressive product (after production) were entered at each of the distinctive points. Additionally a pen, a basic set of Mindstorms (some parts were excluded), and a personal computer for programming the behavior algorithm were also provided.

The items entered in the planning sheet were as follows:

Ideas on a robot
• A shape (design) of a robot.
• Movement of a robot.

Planning on production
• Parts constructing a robot.
• Mechanism of movement.
• An algorithm of the robot's behavior.

Evaluation and analysis of the product
Next planning
The participants were required to follow the following three procedures: (1) To enter an idea on a robot considered in the planning sheet before actually building it; (2) To enter the evaluation and analysis of the product on the planning sheet when completing the idea or trying to add, revise, or change the idea; (3) After that, to enter the next idea on another part of the planning sheet.

After these instructions, the participants freely considered their ideas and created a robot. Throughout the experiment, the participants were required to verbalize their thinking as well as possible. The period of the experiment continued for about four hours.

ANALYSIS OF THE DEGREE OF EXCELLENCE
First, for clarifying in which aspects the work produced by the experts were excellent, we evaluated the degree of excellence of the projects that the participants created. Figure 1 shows photos of the experts' work and the summary of the robot's movement. Figure 2 shows those of the novices.

A Method of Evaluation
The projects were evaluated from the viewpoint of both their originality and practicality. These two points were also used by Finke [3]. The concrete contents of the evaluation from each of the two viewpoints were as follows:

Originality
• The originality of a design: The design is new and is interesting or beautiful.
• The originality of movement: The movement is new and is interesting or beautiful.

Practicality
• The degree of completion of the product: To what degree the ideas considered have been embodied.

Originality was estimated by 63 undergraduates. The procedure was as follows. The evaluators were given photos of the projects
and explanations of their movement by the experimenter. The degree of originality of the design and movement of each work on a 1 to 5 scale was then entered on the evaluation sheet including the photos and explanations. The period of estimation was not restricted.

The practicality of each final product was objectively estimated by the authors. The criterion on the evaluation was as follows:

Level 1: The robot never moves.
Level 2: Only local mechanisms of the robot, such as gears and motors, can move.
Level 3: The robot can move only within a short distance.
Level 4: The robot can continue to act by repeating simple movement.
Level 5: The robot can act by embodying complex body movements, such as turn and reverse.

The Results of the Evaluation

Originality

We first compared the originality of the experts' work with the novices' work. Figure 3 shows the results of the estimation of originality of the design for each work, and Figure 4 shows the results of the originality of movement. The horizontal axis indicates each of the participants ("n1" means novice participant #1 and "e1" means expert participant #1) and the vertical axis indicates the average scores on originality estimated by the 63 graduates.

Figure 1. The experts' projects and their movement.

(e1) The robot moves like a measuring worm with three legs.
• It can continue to walk along a line using another leg at the back of the body.
• It can reverse its direction of movement using two feelers.

(e2) The robot moves by vibration, caused by two arms that spin at extremely high speed.
• It can continue to move along a line.

(e3) The robot moves like a turtle with two legs.
• It can continue to move along a line.

Level 1: The robot never moves.
Level 2: Only local mechanisms of the robot, such as gears and motors, can move.
Level 3: The robot can move only within a short distance.
Level 4: The robot can continue to act by repeating simple movement.
Level 5: The robot can act by embodying complex body movements, such as turn and reverse.
(n1) The robot moves like a grasshopper, making the back legs jump.

(n2) The robot moves by shifting the center of gravity of the body and rotating each of its two legs alternately.

(n3) The robot moves with two arms crawling.

(n4) The robot moves by rotating two gears as wheels while rotating two arms.

**Figure 2.** The novices’ projects and their movement.

**Figure 3.** The estimation of the originality of the design of the experts’ and novices’ work.

**Figure 4.** The estimation of the originality of the movement of the experts’ and novices’ work.
The results show that the novices can be divided into two groups. The scores of the first group comprising n1 and n2 were equivalent to or higher than those of the experts; on the other hand, the scores of the second group comprising n3 and n4 were lower than those of the experts. However, generally speaking, the difference of the scores between the novices and the experts was not significant.

Practicality
Next, we analyzed whether or not we could find a difference in practicality between the experts and novices. Table 1 shows the score of each work evaluated by the authors.

The table shows that all of the experts reached the highest score (i.e., 5), indicating the achievement of complex movement, whereas none of the novices created work that embodied that kind of movement.

The above findings imply the following points. We cannot find a difference between the novices' and experts' performances when simply comparing the originality of their work. The difference, however, becomes significant when we take both their originality and practicality into consideration. For example, one of the novices, n1, whose score on the originality of the design was the highest and exceeded that of the experts, could not produce a robot that actually moved. On the other hand, a novice, n4, did produce work that actually moved, but the originality of the work was definitely low. These results show that the novices could not create work that fulfilled both high originality and practicality simultaneously, but that the experts could.

| Table 1. The scores on the practicality of the experts' and novices' works. |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                 | Expert e1 e2 e3 | Novice n1 n2 n3 n4 | Practicality |
| Concept         | 5              | 5              | 5              | 3              | 2              | 4              |

ANALYSIS OF CREATIVE PROCESS
We confirmed that the experts could produce better projects than the novices based on a comparison of their work. We next discuss how the experts embodied their ideas through the interaction between the mental and external activities. More concretely, we analyze how the experts embodied their ideas (the activity from the mental operation to the external operation) and how the experts received feedback from the result of their production (the activity from the external operation to the mental operation). To do so, we compare the creative process of the experts and novices based on the protocol analysis.

A Schema for Description
First, we explain a method for describing the participants' creative process. In the description, we suppose three stages, Concept, Planning, and Trial, of the interactive process between the mental and external operations, as depicted in Figure 5. Each of the stages is concretely explained as follows.

Concept
As an early stage in the mental operation, the global idea on a product, called the concept, is considered. Activities related to the concept are divided into the two activities:

- Design: Considering the global design of the robot.
- Function: Considering basic functions, such as movement, of the robot.

Planning
As a later stage in the mental operation, concrete procedures for embodying the concept, called planning, are considered. Activities related to the planning are divided into the following three activities:

- Parts: Considering the parts constructing a part of the robot, such as an arm and a leg, and the configuration of the parts.
- Mechanism: A mechanism comprising motors and gears for embodying the movement of the robot.
- Algorithm: A program controlling the behavior of the robot.

Trial
After the mental operation, the external operation for embodying the planning is conducted. We call this manipulation the trial. In this manipulation, the participants engage in physical activities, such as building blocks and constructing a program with a computer. Activities of the trial are divided into the three categories, Parts, Mechanism, and Algorithm, in the same way as planning.

We describe on this schema the creative process of the participants by labeling each segment of the participants' verbalizations and behaviors, and each content depicted on the planning sheet.

Example
Table 2 and Figure 6 show an example behavior of an expert, e3, where e3's verbalizations and drawings depicted on the planning sheet are extracted with the correspondence of each segment to each phase of the schema in Figure 5.

First, the expert, e3, considered a concept where the robot moves with four legs like a turtle (verbalizations #9 and #10). Then, for embodying the concept, he conducted planning in the order of a mechanism (#12), parts (from #17 through #29), and an algorithm (from #27 through #29). Last, he tried to embody the mechanism in trials (from #38 through #40). Figure 6 (a) shows the drawing of this planning.
I will put two motors on each side of the body. Where should I place RCX? I may put RCX on this top. If I make a turtle, I need to make a head. I may try to make a tail. Making the robot trace a line. The robot turns left if it detected black. If the robot detected white, it turns right. I use two motors. And four 40-teeth gears. Then two 8-teeth gears. I prefer walking with two legs. A way of how to attach this is important. Put RCX inside the body. Put RCX beneath the body. The robot goes straight on if it detected brightness. Motor C. Then, a touch sensor.

Table 2. Example verbalizations of expert e3.

<table>
<thead>
<tr>
<th>Protocol segment</th>
<th>Mental operation</th>
<th>External operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concept</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>Function</td>
</tr>
<tr>
<td>9</td>
<td>Like a sea turtle.</td>
<td>o</td>
</tr>
<tr>
<td>10</td>
<td>Walking with four legs.</td>
<td>o</td>
</tr>
<tr>
<td>12</td>
<td>I will put two motors on each side of the body.</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Where should I place RCX?</td>
<td>o</td>
</tr>
<tr>
<td>18</td>
<td>I may put RCX on this top.</td>
<td>o</td>
</tr>
<tr>
<td>19</td>
<td>If I make a turtle, I need to make a head.</td>
<td>o</td>
</tr>
<tr>
<td>20</td>
<td>I may try to make a tail.</td>
<td>o</td>
</tr>
<tr>
<td>27</td>
<td>Making the robot trace a line.</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>The robot turns left if it detected black.</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>If the robot detected white, it turns right.</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>I use two motors.</td>
<td>o</td>
</tr>
<tr>
<td>39</td>
<td>And four 40-teeth gears.</td>
<td>o</td>
</tr>
<tr>
<td>40</td>
<td>Then two 8-teeth gears.</td>
<td>o</td>
</tr>
<tr>
<td>(b) — 113</td>
<td>I prefer walking with two legs.</td>
<td>o</td>
</tr>
<tr>
<td>118</td>
<td>A way of how to attach this is important.</td>
<td></td>
</tr>
<tr>
<td>(c) — 189</td>
<td>Put RCX inside the body.</td>
<td>o</td>
</tr>
<tr>
<td>197</td>
<td>Put RCX beneath the body.</td>
<td>o</td>
</tr>
<tr>
<td>433</td>
<td>The robot goes straight on if it detected brightness.</td>
<td>o</td>
</tr>
<tr>
<td>434</td>
<td>Motor C.</td>
<td>o</td>
</tr>
<tr>
<td>435</td>
<td>Then, a touch sensor.</td>
<td>o</td>
</tr>
</tbody>
</table>

Figure 6. Example drawings of expert e3.
The initial idea was not completed as it was. For instance, he changed the mechanism from movement by four legs into that by two legs (#113; see Figure 6 (b)), revised the configuration of the parts (#189; see Figure 6 (c)), and revised the algorithm (#433). This example shows that the expert, e3, completed his work fulfilling his final idea through the repeated interaction between the mental operation, such as planning, and the external operation, such as trials.

**The Result of Analysis**

We discuss the differences in the creative process of the experts and novices by comparing the characteristics of interaction between the mental operation and the external operation based on the description schema proposed for the foregoing section. As a result, the following four points were identified.

**Finding #1: Proposing a global idea in the initial stage of the creative process**

First, we discussed how the experts considered their concepts, especially in the initial stage of building a robot, and proposed their planning for embodying the concepts in the mental operation of considering ideas. To do so, we analyzed the contents written on the first piece of the planning sheet, and the participants’ verbalizations while engaging in filling in the first piece. Based on the analysis, we identified which element corresponding to each stage of the description schema was focused on by the participants (see Table 3). Table 3 shows that the experts, e1 and e3, discussed all of the elements corresponding to the activities of considering the concepts and planning. Especially, in planning, none of the novices considered all of the stages, whereas all of the experts did. These findings suggest that the experts globally considered their concepts on the products and also comprehensively conducted their planning for embodying the concepts when considering their initial ideas, and based on these global considerations they embodied their ideas.

**Table 3.** The elements of ideas verbalized or depicted on the first piece of the planning sheet.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Expert</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e1</td>
<td>e2</td>
</tr>
<tr>
<td>Design</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Function</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Parts</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Mechanism</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Algorithm</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>

**Finding #2: Revising comprehensively each of the elements of a plan**

Second, we investigated how the experts revised each of the elements constructing their planning when receiving negative feedback from a trial, that is, failing to embody their planning in the external operation. Table 4 shows the number of revisions of the same element in planning, the element operated in the trial immediately before the planning, and the number of revisions of one of the different elements. For instance, the activity revising the mechanism element in planning, after failing in the realization of the mechanism in a trial, corresponds to the former type of revision. On the other hand, the activity revising the algorithm element in planning corresponds to the latter type of revision.

As a result, the novices, n1 and n3, revised only the same element as the one operated in the previous trial, whereas all of the experts revised other elements in addition to the same element. This implies that the novices conducted revisions of planning based on the one to one correspondence in the elements of planning. On the other hand, the experts conducted this type of activity by considering comprehensively the relationship among those elements.

**Table 4. The number of revisions of same/different elements in Planning, compared to the previous Trial.**

<table>
<thead>
<tr>
<th></th>
<th>Expert</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e1</td>
<td>e2</td>
</tr>
<tr>
<td>Same element</td>
<td>19 20 32</td>
<td>20 12 25</td>
</tr>
<tr>
<td>Different element</td>
<td>3 4 6</td>
<td>0 2 0</td>
</tr>
</tbody>
</table>

**Finding #3: Aggressive improvement of planning**

Third, we analyzed which type of feedback gave the experts the chance of revising their ideas while receiving a result of the realization in the external operation. Table 5 shows the number of revisions in planning with and without negative feedback (that is, negative estimation failing in embodying a plan).

As a global tendency, the experts revised their plans more than the novices did. Moreover, focusing on the revision activity without negative feedback, the novices tended to revise their planning only when receiving negative feedback; however, the experts revised without negative feedback, that is, when succeeding in the realization of planning. This seems to reflect the experts’ aggressive activity of revising their planning, and this type of activity may promote the cycle of the mental and external operation.

**Table 5.** The number of revisions in Planning with/without negative feedback.

<table>
<thead>
<tr>
<th></th>
<th>Expert</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e1</td>
<td>e2</td>
</tr>
<tr>
<td>With feedback</td>
<td>22 36 26</td>
<td>12 27 14</td>
</tr>
<tr>
<td>Without feedback</td>
<td>8 14 8</td>
<td>0 3 2</td>
</tr>
</tbody>
</table>

**Finding #4: Focusing on valid viewpoints**

Finally, we investigated which type of viewpoints the experts focused on while embodying their ideas in the planning as mental operation, and estimated the result of realization of the ideas in a trial as external operation. Table 6 shows which of the viewpoints listed in the table was mentioned in their mental and external operation. The existence or absence of each item was determined based on the participants’ drawings depicted on all of the planning sheets and their verbal protocols. These viewpoints are considered to be important for building a robot.

The global characteristics show that the experts mentioned more viewpoints than the novices. Moreover, the experts focused on all of the important elements for building a robot, such as global design (e.g., the center of gravity and balance), the viewpoint of parts (e.g., the number of parts), and the viewpoint of mechanism.
Features of experts' creative process

The characteristics of the experts' creative process can be summarized as the following points. First, the experts embodied their ideas while taking total aspects of the concepts and planning into consideration, especially in the early stage of their creative process (Finding #1). Second, they revised their ideas, considering comprehensively the relationship among the different functions constructing a single planning, such as parts, a mechanism and an algorithm, when receiving negative feedback from the external operation (Finding #2). We define each of these two activities as the activity directed from mental toward external operation and the activity from external toward mental operation, respectively. Therefore, these findings support that the experts comprehensively conducted these two kinds of activities, each of which has a different direction, and these activities promoted the interaction between the mental and external operations in a complex creative task that had to fulfill multiple constraints underlying both mental and external phases simultaneously.

Moreover, the experts tended to revise their plans even though they succeeded in embodying the planning (Finding #3). This means that they could autonomously control the interaction between the mental and external operations, not depending on negative feedback as a cue for reconstruction from the external world. In addition, the experts focused on various important features for building a robot, some of which are attributed to the physical world, such as the center of gravity, balance, and the number of parts, throughout their creative activity (Finding #4). This also means that they could engage in the mental operation utilizing multiple valuable information for actually embodying the planning into the physical world.

CONCLUSIONS

In the early part of this paper, we confirmed, based on the comparison of the degree of excellence of the novices' and experts' work, that the experts could create projects that fulfilled both high originality and practicality simultaneously, but that the novices could not. We then moved to a more detailed analysis of the creative processes of the work based on the protocol analysis. The result implied that (1) the experts globally considered their concepts of the products and also comprehensively conducted their planning for embodying the concepts when considering their initial ideas, (2) the experts reconstructed their planning by considering comprehensively the relationship among the different functions constructing a single plan, (3) the experts' aggressive activity of revising their planning may promote the cycle of the mental and external operations, and (4) the experts were able to embody successfully their ideas by focusing on various aspects of important viewpoints and also were able to extract valid information from the feedback from the external to mental operation by analyzing the result of the embodiment from multiple viewpoints.

REFERENCES


Table 6. The viewpoints mentioned in the mental and external operations.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Expert</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of gravity and balance</td>
<td>me me e me me</td>
<td>me me e me me</td>
</tr>
<tr>
<td>Friction and resistance</td>
<td>me me me m me</td>
<td>me me me me m</td>
</tr>
<tr>
<td>Strength</td>
<td>me me me me m me</td>
<td>me me me me me</td>
</tr>
<tr>
<td>Symmetry</td>
<td>me me me me m</td>
<td>m</td>
</tr>
<tr>
<td>Weight</td>
<td>m me m m m</td>
<td>m me m m</td>
</tr>
<tr>
<td>Number of parts</td>
<td>m me me m me m</td>
<td>m me m m</td>
</tr>
<tr>
<td>Specific parts</td>
<td>m m m m</td>
<td>m m</td>
</tr>
<tr>
<td>Individual specificity</td>
<td>me</td>
<td>m</td>
</tr>
<tr>
<td>each motor</td>
<td>me</td>
<td>m</td>
</tr>
<tr>
<td>Interference</td>
<td>m me m</td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>me me m</td>
<td></td>
</tr>
<tr>
<td>Resonance</td>
<td>e</td>
<td></td>
</tr>
</tbody>
</table>

m: mental operation  
e: external operation