Received 21 March 2024, accepted 17 April 2024, date of publication 29 April 2024, date of current version 8 May 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3394502

RESEARCH ARTICLE

Co-Thinking Device for Simultaneous Support of Human Cognitive and Physical Functions

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This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Research Fellowship under Grant 23H03440.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the Faculty of Medicine at Saga University under Application No. R1-70.

ABSTRACT In this paper, we propose a novel system in which a human and a device work in unison on a single task with the aim to simultaneously support human cognitive and physical functions. In this system, the cognitive and physical burdens of the task are shared between the human and device, with the human understanding the entire task and performing rough upstream actions. Additionally, the device understands the surrounding environment, objects, and the human and executes detailed downstream actions. A prototype device was developed to assist in solving silhouette puzzles that abstract and generalize cognitive and physical tasks. The prototype is a pen-shaped device held in the user's hand. The device picks up puzzle pieces and rotates them to the appropriate position. A display is placed in front of the user and provides feedback information for communication between the system and user. Experiments showed that the proposed device reduced the time required to solve these puzzles. Furthermore, the work was found to be accurate with no errors, and the time required was stable with no irregularities. The subjective evaluation results using the NASA Task Load Index showed that the proposed system can decrease mental load and burden. Moreover, it was confirmed that the human and device must communicate with each other to work simultaneously on one task. In conclusion, the proposed device can support human cognitive and physical functions simultaneously.

INDEX TERMS Assistive device, collaborative robot, co-thinking device, image recognition, mental load, human augmentation, silhouette puzzle, work performance.

I. INTRODUCTION

The decline in cognitive and physical functioning with age is an inevitable and natural phenomenon in humans. Moreover, some people have difficulty with these functions because of disabilities or diseases. In general, many individuals require help with their work and daily activities. These are common concerns that will need to be increasingly considered in the future, as people will live longer owing to advances in medical technology [1], [2], [3]. Furthermore, even without a decline in cognitive or physical function, fatigue, inattention, habituation, and pride often cause human errors, leading to mistakes and accidents, during work [4], [5], [6], [7].

The associate editor coordinating the review of this manuscript and approving it for publication was Maria Chiara Caschera.

Supporting cognitive and physical functioning through technology is extremely important for enhancing people's safety, security, and affluent lifestyles, and research and development of such technology are expected. For example, augmented reality and mixed reality have been proposed as devices that support cognitive function, whereas power-assist devices have been proposed to support physical function. Some supporting technologies have already been implemented in society; however, not all individuals adopt them.

For example, older adults are generally less receptive to new technologies, such as new devices and machines. State-of-the-art technologies, such as augmented reality and mixed reality, that support cognitive functions are rare. Graphical user interfaces, in which information is presented unilaterally on a display, are also typical for devices that

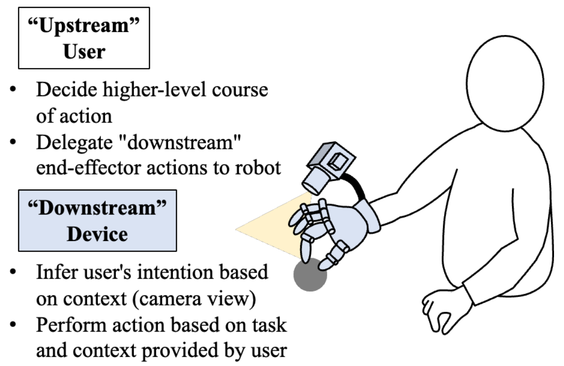


FIGURE 1. Concept of the proposed device.

are difficult for older adults to use (e.g., train ticket vending machines). In addition, when operating power-assist devices, people unfamiliar with the technology often need help understanding the assistive mechanism, which results in inadequate performance.

As there is often a correlation between the decline of cognitive and physical function, supporting only one of these functions using conventional technology may be insufficient. For example, supporting only cognitive or physical function may confuse older adults. By naturally and gently supporting both functions simultaneously, it is expected the support will be accepted by many people, similarly to people supporting each other out of consideration.

This study explores the possibility of supporting both cognitive and physical functions simultaneously. As shown in Figure 1, we propose a novel device that can be worn in series with a human, enabling the two to work on a single task as an integrated whole. In the proposed system, the cognitive and physical burdens of the task are shared between the human and the device, with the human understanding the entire task and performing the rough upstream actions. The device understands the surrounding environment, objects, and the human and executes detailed downstream actions. Devices equipped with sensors and AI are capable of faster and more accurate recognition and judgment than humans. Moreover, such devices often have AI-driven actuators and can move more regularly and stably than humans. However, humans can make more flexible decisions than devices. Thus, we propose a system, in which humans and devices work together, negotiating about cognition, planning, and execution as they perform tasks, with the human retaining ultimate control of the work: the human takes the initiative in executive decision-making and adjusting the tempo of the work.

An advantage of the proposed system is that collaboration between the proposed device and humans is expected to reduce the workload of humans and shorten their work time. It is also expected that the system will be able to perform accurate and error-free work in an even and stable manner.

In this paper, we propose the concept of a co-thinking device that simultaneously supports human cognitive and physical functions and show its validity through experiments. We construct a prototype device and use it to support an individual in performing a task that requires cognitive and physical functions (solving a silhouette puzzle). The remainder of this paper is structured as follows: Section II introduces related research, Section III describes the task and system, and Section IV presents the experiments conducted to verify the effectiveness of the proposed device. Then, Section V provides a discussion, and Section VI concludes the paper with a summary.

II. RELATED WORKS

Augmented-reality and mixed-reality technologies are currently being researched and developed to support human cognitive functions [8], [9], [10], [11]. These technologies use a transparent display similar to a pair of glasses that is attached to the user's head. The device is equipped with an image sensor that can capture the surrounding environment and superimpose various types of information onto the captured image using image information processing. This allows users to perceive information that would otherwise be visually unrecognizable. However, augmented-reality and mixed-reality technologies support only cognitive aspects and not physical functions.

By contrast, body-worn power-assist devices that support physical functions declining due to aging or disability have also been studied and developed [12], [13], [14]. These devices can reinforce joint and muscle strength when worn on the user's upper or lower limbs, thereby enabling exercise beyond the user's original physical strength. However, these devices are only primary–secondary devices that operate according to movement commands from the user and are limited to supporting physical functions. The devices do not have any function to recognize the environment or objects or to autonomously make decisions about their actions. Therefore, augmented-reality, mixed-reality, and power-assist technologies require users to understand and become accustomed to their operation methods, making it difficult for inexperienced and older users to immediately primary their use.

Research and development of robots that cooperate with humans have been conducted in the following areas: [15], [16], [17], [18], [19]. Although cooperative robots share a workspace with humans, they typically work on separate subtasks. Robots tend to perform repetitive tasks that are tedious, burdensome, dangerous, and require high precision and strength. By contrast, humans tend to perform relatively easy and less burdensome tasks that require flexibility and adaptability. A major challenge in this system is the need to design the content and division of work before it begins.

Cooperative robots may indirectly support human cognitive and physical functions. However, in general, the mutual involvement of cooperative robots and humans during work is designed to be relatively low, and contact between them tends to be avoided due to safety concerns. Thus, cooperative robots do not support human cognitive and physical functions directly or simultaneously.

In recent years, research on cooperative robots that recognize work processes in real time, communicate with workers, and attempt to work efficiently with both of them has begun to attract attention [20], [21], [22]. These studies aimed to develop frameworks for cooperative robots and humans to communicate, propose solutions to each other, negotiate, and take complementary actions, similarly to human cooperation. If such research and development advance, then cooperative robots and humans can coordinate subtasks and work efficiently without prior instructions. In this case, the cooperative robot must understand the task and human behavior and integrate them into its action plan. In addition, the cooperative robot must be able to provide feedback to the human through verbal and nonverbal communication for the human to accurately understand the cooperative robot's action goals.

Recent advances in AI have considerably affected the study of cooperative robots. Thus, it is becoming possible to generate solutions for multiple work goals [23], [24]. However, the design of interactions between humans and cooperating robots to achieve intuitive and natural cooperation in real time still requires further investigation. Moreover, the effect of such cooperation on work performance and human mental load/burden needs to be clarified. Therefore, further research and development are highly anticipated.

Our research group has been researching and developing myoelectric prosthetic hand systems for persons with amputations [25], [26], [27], [28], [29]. In recent years, we explored advanced control techniques for myoelectric prosthetic hands by introducing vision sensors and image recognition functions into the prosthetic hand. During research, we conceived the idea of extending the use of the system not only to persons with amputations but also to a wide range of healthy people [30]. Therefore, in this paper, we propose an assistive device that physically supports the person performing the task and facilitates the intellectual aspects related to the task, that is, a type of assistive device that cooperatively co-thinks with the user about how to solve the problem.

III. DESIGN OF THE CO-THINKING DEVICE

A. TARGET TASK

This study used silhouette puzzle problems as tasks requiring both intellectual and physical functions. In the silhouette puzzle problem, the shape of the silhouette is presented to the player, who puts the puzzle pieces together to form the same shape as the silhouette (Figure 2). The used puzzle pieces were tetrominoes consisting of four squares.

The abilities generally required to solve silhouette puzzles are shown in Figure 3. They include recognizing the shape of the silhouette puzzle and puzzle pieces, recognizing where and how to rotate and fit the puzzle pieces, planning the motion to determine the order in which to assemble the puzzle pieces, memorizing the solution procedure by trial and error, and grasping, rotating, and moving the

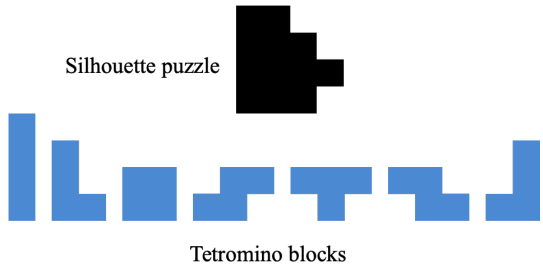


FIGURE 2. Overview of the Silhouette Puzzle.

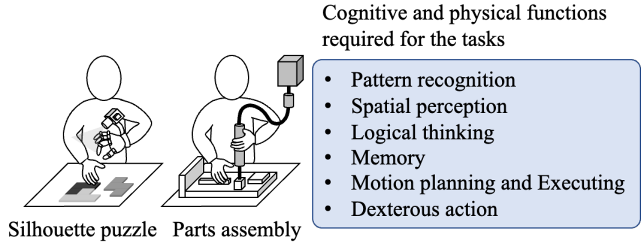


FIGURE 3. Capabilities required for solving silhouette puzzles and their relationship with other tasks.

puzzle pieces. Assembly, picking, packaging, and inspection tasks in manufacturing and distribution industries require similar abilities. For example, the operator correctly identifies individual parts and places them in predetermined positions and angles in assembly tasks. In many cases, the parts must be assembled in sequence. The worker usually memorizes the steps of these tasks and performs them according to the assembly procedure. In this study, silhouette puzzles were employed to abstract and generalize these tasks and to quantitatively evaluate the performance of the device.

B. SYSTEM COMPONENTS

The proposed system is a pen-shaped device held in the user's hand (Figure 4). The device is a grasping and rotating tool that picks up puzzle pieces and rotates them to the appropriate position. A display is placed in front of the user to provide feedback for human communication with the system. Above the workspace is a camera that monitors the assembly of the puzzle; through it, the system constantly monitors and understands the assembly process.

Figure 5 shows the configuration of the system. A pen-shaped device (height: 13.5 cm, width: 5.0 cm, weight: 65.0 g) is equipped with a solenoid magnet (TMEH-A1, TRUSCO NAKAYAMA CORPORATION) for grasping puzzle pieces (size: 2.0-8.0 cm, weight: 8.0 g) and a servomotor (SG-90, JAPAN ROBOTECH LTD) for rotating them. Embedded on the side of the device is a small tact switch that controls the grasping of puzzle pieces. The servomotor can be used to rotate a grasped puzzle piece at 90° intervals using a pulse width modulation signal. The microcontroller is connected via USB to a central control computer (Victus 16-e1065AX, HP Japan Inc.). A camera (C920nHD Pro Web Camera, Logicool Co Ltd.) placed above

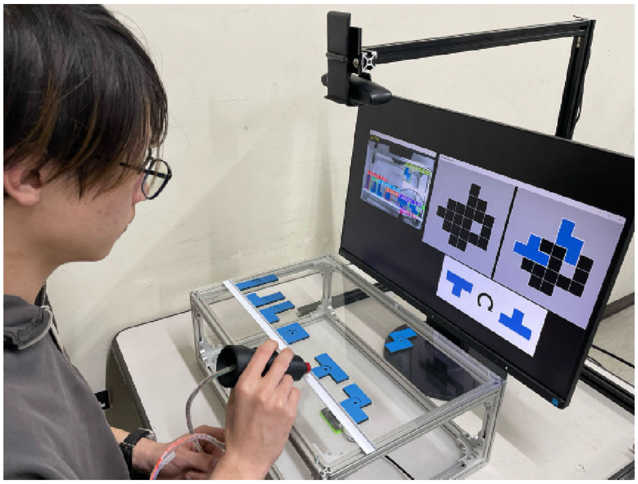


FIGURE 4. Scenes of the system use.

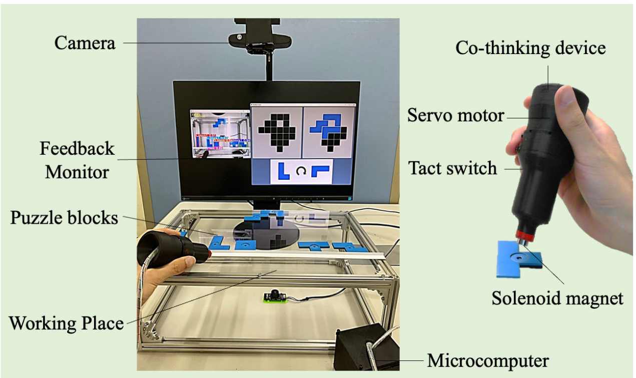


FIGURE 5. System configuration.

the work environment is also connected to the central control computer. The central control computer recognizes the puzzle pieces, searches for silhouette puzzle solutions, and generates control signals for the pen-shaped device. The display (Flex Scan EV2455, EIZO Corporation) is connected to the central control computer. It interactively presents the solution procedure calculated by the central control computer, puzzle-piece recognition results, and puzzle-solution progress to the user.

Next, we explain how the user and system work together. First, the system recognizes the silhouette puzzle problem and all the puzzle pieces to be used for the solution from the camera image. It uses a search program to derive a solution and calculate the puzzle pieces required for the solution and the angle at which they should be rotated. The display then shows the puzzle pieces required for the solution and the solution procedure to the user. The user refers to the system suggestions during the work. Additionally, the camera recognizes the tip of the pen-shaped device, and the system observes its movement. The system understands the progress of the task by referring to the movement of the pen device and the solution procedure. For example, when a user moves

Algorithm 1 Brute-force search algorithm

```
while there are tiles remaining in question do
    if error pattern exists then
        return search failed
    while tetromino blocks can be placed do
        change tetromino blocks
        match tetromino blocks
        remove matched blocks from question tile
```

FIGURE 6. Pseudo code for puzzle-solution search.

the tip of the pen device close to a puzzle piece, the system automatically recognizes the piece and determines whether the piece is required for the solution. If so, the system informs the user with a beep. Moreover, a piece of metal is embedded in the center of each puzzle piece, and a solenoid magnet embedded in the tip of the pen-shaped device is used to attract the puzzle piece. The timing of lifting the puzzle piece is indicated by the user through a tact switch. In other words, the final initiative for the work rests with the user who makes decisions regarding the execution and controls the work tempo. The solenoid magnet is turned on only when the system determines that the puzzle piece is required to solve the puzzle; it is not turned on when the tact switch is pressed if the piece is not necessary for solving the puzzle. Once a puzzle piece is picked up, the system automatically rotates it to the appropriate angle. During puzzle-solving, the display can show information about the puzzle-solving procedure, the system recognition result of the puzzle piece, and the puzzle-solving status of the user.

C. SIMULTANEOUS SUPPORT OF HUMAN COGNITIVE AND PHYSICAL FUNCTIONS

This section describes how the proposed system provides cognitive and physical support to the user.

1) SUPPORT OF HUMAN COGNITIVE FUNCTION

To support cognitive functions, the system derives solutions to silhouette puzzles faster than humans, communicates with humans via the pen-shaped device and display, and guides humans so that puzzle solutions can be achieved smoothly. Thus, the system reduces the cognitive burden on users. The system also prevents errors such as incorrect puzzle-piece selection or rotation.

The system searches for all the combinations of puzzle pieces for a given problem silhouette and derives a solution. Figure 6 shows the algorithm used for puzzle-solution search.

The central control computer connected to the camera recognizes the puzzle pieces based on deep learning. Figure 7 shows the results of the puzzle recognition based on deep learning. The system can recognize the tetromino types I, J, L, O, S, T, and Z and four orientations: 90°, 180°, 270°, and 360° with high accuracy. YOLO v5, a well-known object-recognition algorithm, is used for recognition [31], [32]. In addition to puzzle recognition, the system determines

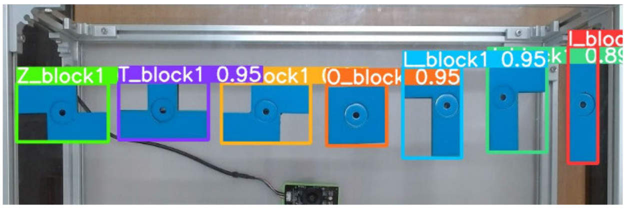


FIGURE 7. Recognition of puzzle pieces based on deep learning.

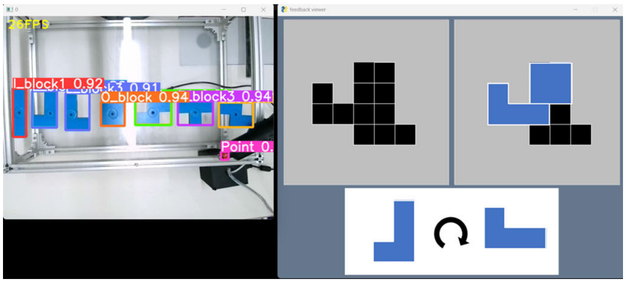


FIGURE 8. Feedback screen: left side shows the puzzle-piece recognition results and the puzzle solution camera image; right side shows the solution calculated by the central control computer and the solution procedure displayed in an animation.

whether each puzzle piece is used to solve the puzzle, and if so, how it will be rotated.

In the proposed system, the human and the system must communicate to work together. The display in front of the human interactively presents a feedback screen, which depends on the state of the work as Figure 8. The feedback screen is continuously updated with new information as the puzzle pieces are assembled.

2) SUPPORT OF HUMAN PHYSICAL FUNCTION

To assist with physical function, the pen-shaped device assists the user in picking puzzle pieces up from a desk and rotating them in the appropriate direction. The device reduces the difficulty of picking up thin puzzle pieces that stick to the desk and are sometimes challenging to pick up with fingers. Additionally, the device allows the user to select the correct puzzle piece from combinations such as J-L and S-Z, which can be confusing depending on the angle of view, and make decisions such as clockwise/counterclockwise rotation without confusion. This also results in fewer errors.

Figure 9 shows the puzzle-piece hardware mechanism, grasping, and turning. The tip of the pen-shaped device is a solenoid magnet, which, when turned on by a command from the tact switch, can attract the metal piece installed at the center of the puzzle piece and thus lift the puzzle piece. The solenoid magnet is connected to a servomotor whose rotation angle is automatically controlled by a pulse width modulation signal from a microcontroller.

IV. EXPERIMENTS

A. CONDITIONS

An experiment was conducted to verify the validity and usefulness of the proposed system. Ten subjects (age: 22.6±1.3, male/female: 7/3) participated in the experiment. The participants were given a thorough explanation of the purpose and methods of the experiment, and a consent form was signed by each participant before the experiment. This experiment was conducted with the approval of the Saga University Ethics Review Board (R1-70). A tabletop (height: 30.0 cm, width: 45.0 cm) was placed in front of each participant (Figure 4). The participants were allowed to move only one puzzle piece at a time.

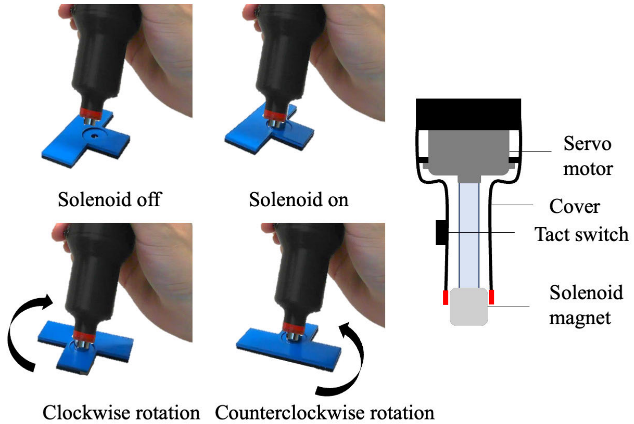


FIGURE 9. Grasping and rotating functions of the device: right side shows the pen-shaped device; left side shows puzzle pieces rotated clockwise and counterclockwise in 90° increments.

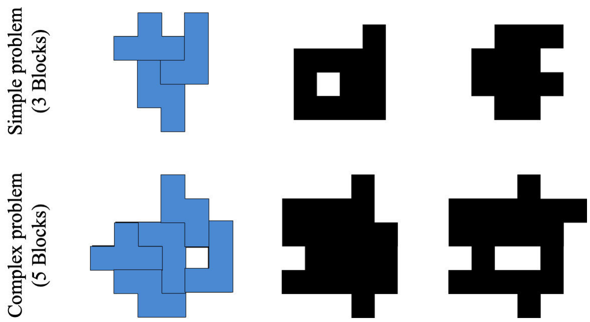


FIGURE 10. Examples of problems with different difficulty levels.

Six types of tetrominoes (I, J, L, S, T, and Z) were used to create the silhouettes. Two types of silhouette problems were presented (Figure 10): simple problems using three tetrominoes and complex problems using five tetrominoes, with three problems for each. The puzzle pieces used for the solution were arranged such that on average 4.9 edges (minimum: 4 edges, maximum: 6 edges) of the edges touched each other for the simple problem and 10.6 edges (minimum: 10 edges, maximum: 11 edges) of the edges touched each other for the complex problem to make them less analogous.

To clarify the effectiveness of the proposed system, the participants solved problems by hand and using the proposed system, and the results were compared. In addition, to investigate how the difference in communication between the subject and the system affects the performance, we prepared three different conditions for feedback presented

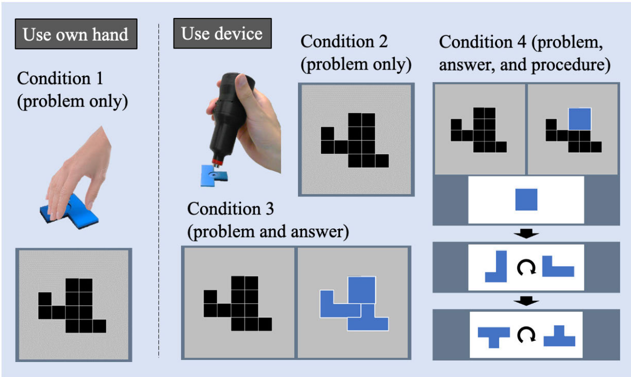
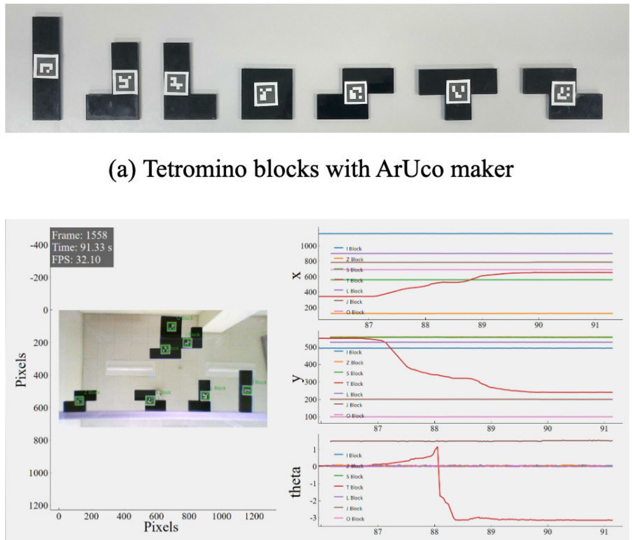


FIGURE 11. Experimental conditions.



(a) Tetromino blocks with ArUco maker

(b) User interface of the monitoring system

FIGURE 12. Monitoring system.

on the display. Four experimental conditions were designed (Figure 11): Condition 1, in which the subject used their own hand; Condition 2, in which only the problem was displayed, and the proposed device was used; Condition 3, in which the problem and solution (placement of completed blocks) were displayed; and Condition 4, in which the problem, solution, and procedure (the puzzle pieces used for the solution and the rotation method of each in a sequence) were displayed. Similarly to Condition 2, only the problem was displayed in Condition 1.

In Condition 2, which was without feedback about the solution or procedure, the subject decided whether to use a puzzle piece by placing the tip of the pen-shaped device close to a certain puzzle piece. If a piece was necessary to solve the puzzle, a beep provided the subject with this information. Once the device attracted the piece, the system automatically rotated it to the appropriate angle.

Condition 1 and Conditions 2–4 were conducted on different days, with at least one day in between. The order of the presented problems was random for simple and complex questions and the feedback method. Before each experiment, the subjects were provided a sample for practice and a sufficient amount of practice before the experiments were conducted. Because some complex problems took a significant amount of time to solve, a time limit of 300 seconds was set, and attempts that exceeded this time limit were terminated as timeouts.

A monitoring system was used to record and analyze the subjects' trials during the experiment. As shown in Figure 12(a), ArUco markers [33] were attached to the backs of the puzzle pieces, and their movements were measured using a camera below through the transparent top panel of the tabletop. ArUco markers are open-source markers that can be used to estimate the orientation of objects they are affixed to, and they are robust in their detection, allowing for quick and easy measurements of the object's position and orientation. Figure 12(b) shows the created interface screen. It records the movement and rotation of all puzzle pieces during the trial in real time, and from the measured data, various indicators, such as the time the subject spent on the trial, the time they touched the block, the time they did not touch the block, and the number of times they touched the block can be calculated.

In addition, the NASA Task Load Index (NASA-TLX) [34], [35], [36] was used to evaluate the subjective mental load and burden of the participants. The NASA-TLX evaluation index consists of six items: mental demand, physical demand, temporal demand, own performance, effort, and frustration level. For these six items, we prepared a questionnaire with a 12 cm line segment with low/high or good/poor poles and asked the participants to mark their positions on the line segment. The position of the mark was interpreted as a numerical value from 0 to 100, which was used as the evaluation score.

B. RESULTS

Figure 13 shows an example of solving a complex silhouette puzzle using the device. The solution is completed in approximately 27 seconds. The colored background indicates the time when the puzzle piece was being manipulated. When the tip of the device was close to the puzzle piece, it was a candidate for selection. When a puzzle piece was required for the solution, the system beeped as feedback to the participant. During this time, the solenoid magnet rotated to its initial position. The participant turned on the solenoid magnet with the tact switch and lifted the puzzle piece. The lifted puzzle piece was automatically rotated to the appropriate angle. In the example in Figure 13, the device did not come into proximity to a puzzle piece that was not required for the solution. However, in the trials it did, no beep as feedback was provided to the participant. Moreover, the solenoid magnet did not rotate to its initial position nor was it turned on when the tact switch was pressed.

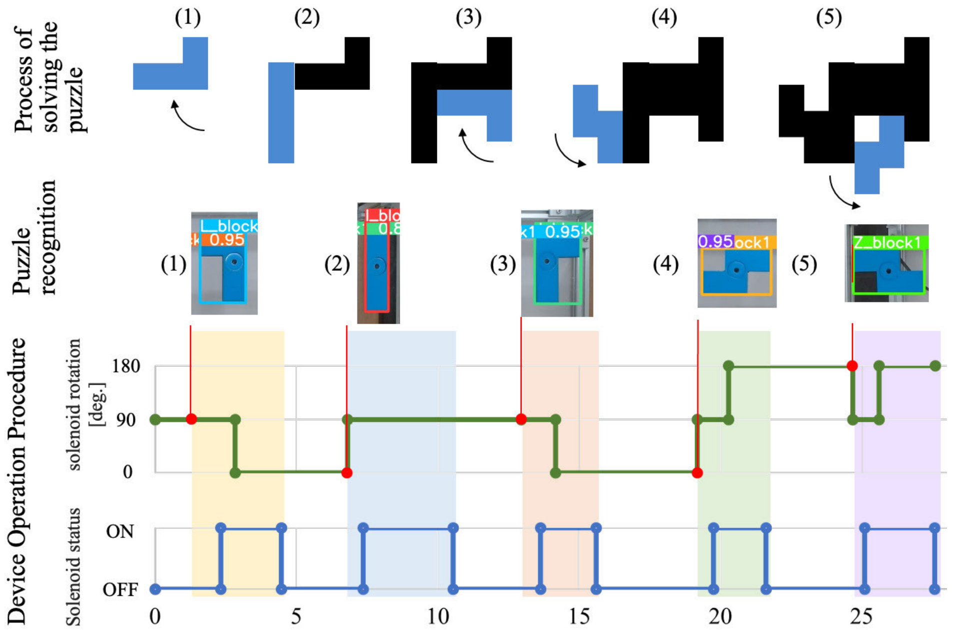


FIGURE 13. Trial example: from the top, the process of assembling the puzzle, the puzzle-piece recognition, the solenoid magnet's angle of rotation, and the solenoid magnet's ON/OFF status. The horizontal axis shows the elapsed time. The device tip was close to the puzzle piece at the point indicated by the red dot.

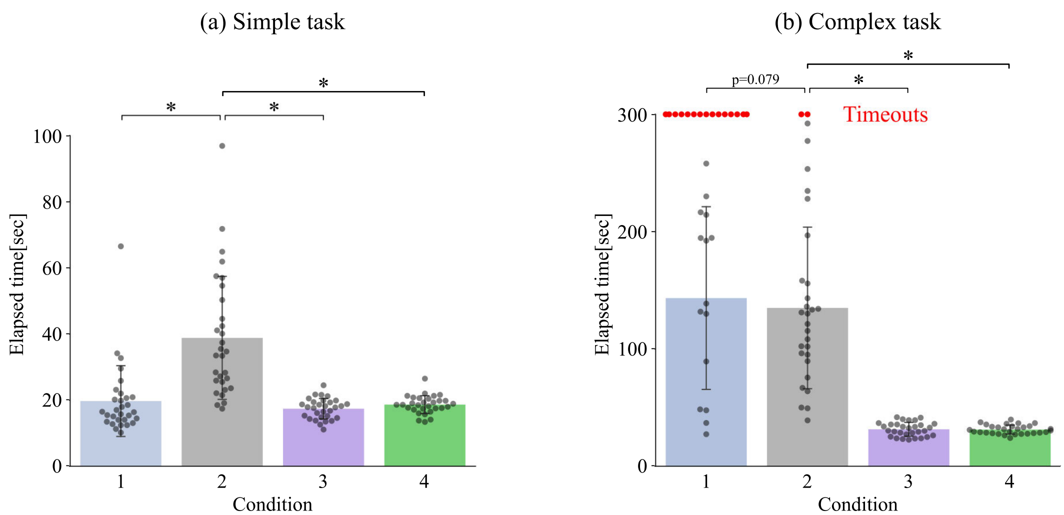


FIGURE 14. Comparison of trial times: the bar charts show the means and standard deviations of 30 trials for 10 subjects, solving the three problems. $*p < 0.05$. The plots indicate the total time required to solve each. However, the red plots indicate the timeouts. Means and standard deviations are calculated excluding these.

The total time required to solve the problems is shown in Figure 14. The bar charts show the means and standard deviations of 30 trials for 10 subjects, solving the three problems. Paired t-tests were performed to determine if the parameter obtained were significantly different between the 4 conditions. Bonferroni correction was used to adjust the p-values to control the family-wise error rate. In the case, Timeout was assumed to have taken 300 seconds. In general, more time was required for complex problems than for simple problems, and the difference was more pronounced in Condition 1, where the subjects used their own hands. When using the device, the time required varied considerably depending on the type of feedback. Condition 2, in which only questions were displayed, required more time. In the case of simple problems, the subjects spent more time in Condition 2 than in Condition 1. For complex problems, many timeouts occurred in Conditions 1 and 2. However, Conditions 3 and 4 showed higher performance for both simple and complex problems compared with Conditions 1 and 2. The standard deviations were small for Conditions 3 and 4. Thus, the effectiveness of the proposed device is high for complex problems.

TABLE 1. Details of trial times: the values show the mean and standard deviation of 30 trials for 10 subjects, solving the three problems. However, for Conditions 1 and 2 of the Complex problem in Table (a), the mean and standard deviation are calculated excluding the timeout trials.

(a) Details of the solution attempts for the silhouette puzzle

Simple problem	Use own hands	Use device		
	Condition 1	Condition 2	Condition 3	Condition 4
Time required for the trial	19.72 ± 10.52	38.82 ± 18.29	17.40 ± 3.04	18.64 ± 2.65
Time holding the puzzle piece	5.20 ± 2.26	12.34 ± 6.29	7.27 ± 1.47	7.28 ± 1.31
Time not holding the puzzle piece	14.52 ± 9.74	26.48 ± 14.07	10.13 ± 2.25	11.21 ± 1.81
Number of times the puzzle piece was touched	3.53 ± 0.99	3.43 ± 0.80	3.10 ± 0.39	3.00 ± 0.00
Complex problem	Use own hands	Use device		
	Condition 1	Condition 2	Condition 3	Condition 4
Time required for the trial	143.36 ± 75.23	134.99 ± 67.62	31.49 ± 5.77	31.26 ± 3.79
Time holding the puzzle piece	14.25 ± 7.11	31.66 ± 19.08	13.58 ± 2.46	12.83 ± 2.36
Time not holding the puzzle piece	129.11 ± 69.07	103.33 ± 61.32	17.92 ± 4.44	18.07 ± 1.95
Number of times the puzzle piece was touched	13.93 ± 8.77	7.11 ± 2.36	5.30 ± 0.52	5.00 ± 0.00

(b) Number of timeouts during solution attempt

Number of timeouts	Condition 1	Condition 2	Condition 3	Condition 4
Simple problem	0	0	0	0
Complex problem	15	2	0	0

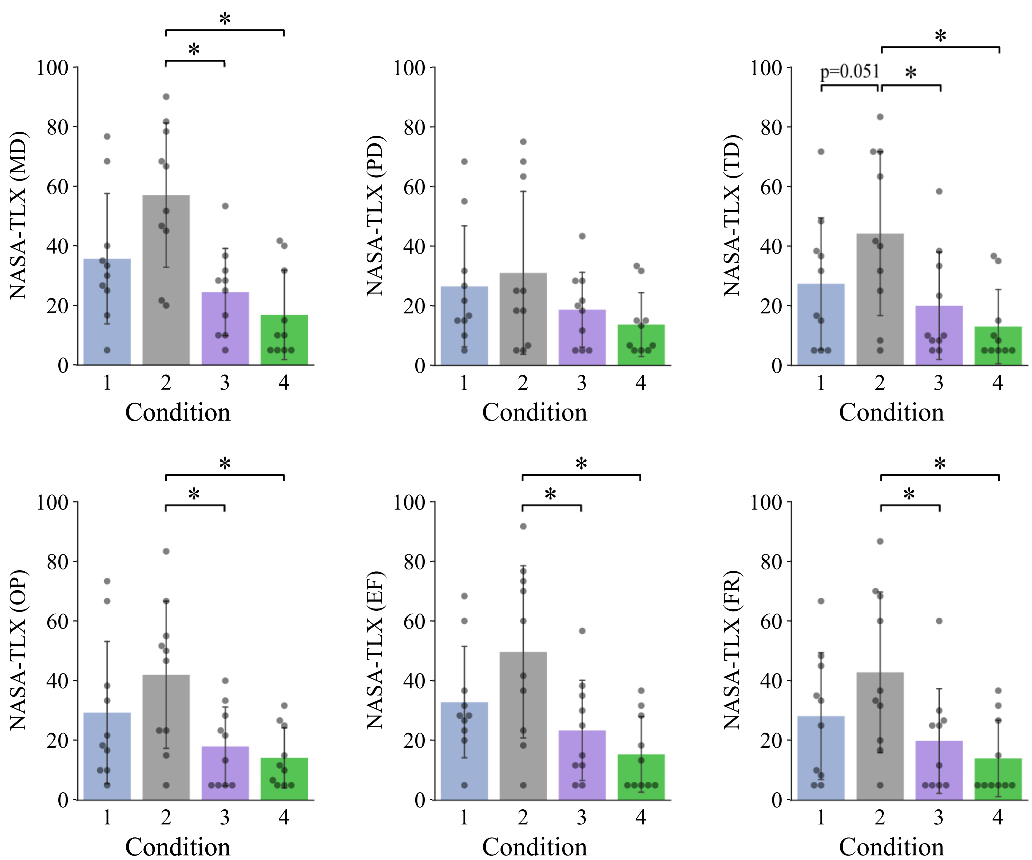


FIGURE 15. NASA-TLX Score (simple problem): MD, mental demand; PD, physical demand; TD, temporal demand; OP, own performance; EF, effort, FR, frustration level. *p<0.05.

Tables 1(a) and (b) show the time required for the trial, the time holding the puzzle piece, the time not holding the puzzle piece, and the number of times the puzzle piece was touched. In (a), the time holding the puzzle piece and the time not

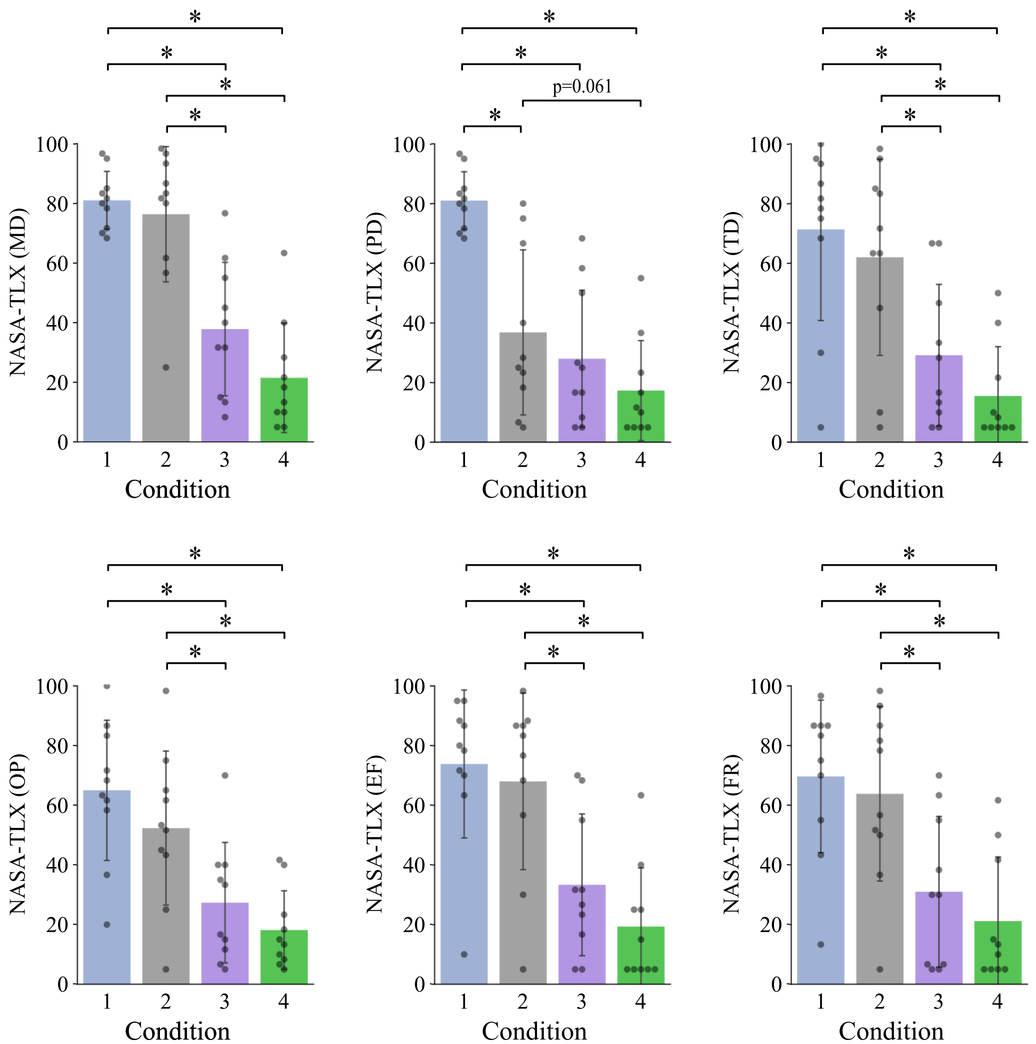


FIGURE 16. NASA-TLX Score (complex problems): MD, mental demand; PD, physical demand; TD, temporal demand; OP, own performance; EF, effort, FR, frustration level. *p<0.05.

holding the puzzle piece were longer and tended to increase for complex problems than simple problems. In particular, the time not holding the puzzle piece in conditions 1 and 2 increased significantly for complex problems than simple ones. The number of times the subject touched the puzzle piece reflects the burden of trial and error while solving the puzzle. It tended to increase when subjects used their hands, and the measured value was more significant for complex problems. In Condition 4, where the device was used to show the solution and the procedure, the number of times the subject touched the puzzle pieces was the smallest, consistent with the number of puzzle pieces used to solve the puzzle. In (b), no timeout occurred for the simple problem, but for the complex problem, timeouts occurred for conditions 1 and 2. In particular, condition 1 resulted in a timeout in 15 trials, half of the total.

Next, Figures 15 and 16 show the results of a subjective evaluation of the subjects' mental load and burden based on the NASA-TLX. Figure 15 shows the results for a simple problem, and Figure 16 shows the results for complex problems. The means and standard deviations of 30 trials of 10 participants solving the three problems were calculated. Paired t-tests were performed to determine if the parameter obtained were significantly different between the 4 conditions. Bonferroni correction was used to adjust the p-values to control the family-wise error rate.

The graph shows that the scores for complex problems were higher than those for simple problems, indicating that the subjects experienced an increased mental load/burden. For simple problems, the reported mental load/burden was not very high, and the score remains fairly low even in Condition 1, in which the subjects used their hands; however, for complex problems, the score was lower when the subjects used the device than when they used their hands. In particular, when the device was used to display the problem, answer, and procedure, the evaluation index scores were consistently low across all problems, indicating that mental load and burden were reduced.

V. DISCUSSION

In this experiment, we addressed the silhouette puzzle problem using our proposed system, which simultaneously supports human cognitive and physical functions. The results showed that the proposed device reduced the time required to solve these puzzles. Moreover, we also confirmed that the proposed device is error-free and accurate and that the time required to solve the puzzles was consistent and stable. Additionally, the results of the subjective evaluation using the NASA-TLX showed that the proposed system can decrease the mental load and burden of humans; thus, the system can support both cognitive and physical functioning during tasks.

The effectiveness of the proposed system was more pronounced for complex problems than for simple ones. The efficiency of the puzzle-solving was consistently improved by using the proposed system.

The feedback conditions of the system had an effect on the performance. Because the proposed system involves a human and a device working simultaneously on the same task, both parties must communicate. Therefore, it was found that the time required for the solution and the mental load/burden were improved by showing the participant the solution and its procedure proposed by the system. It was also confirmed that the work could be performed stably.

The results show that both cognitive and physical functions can be supported simultaneously, which was the objective of this study. Furthermore, it was clarified that information sharing between humans and the system is essential for enhancing work performance.

VI. CONCLUSION

In this paper, we propose the concept of a co-thinking device that simultaneously supports human cognitive and physical functions, and experimentally show its validity. We constructed a prototype device and used it to solve silhouette puzzles.

The experiments showed that feedback from the system was essential for enhancing the work effectiveness. Based on this, we intend to introduce technologies such as augmented reality and mixed reality to realize an intuitive and realistic human–system communication in the future. In addition, we would like to explore the possibilities of the proposed device use for older adults, as well as for people with physical and cognitive disabilities.

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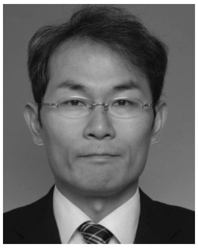

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