Design of Supernumerary Robotic Limb Interface Considering Attention Allocation in Dual-presence Task

Dual-presence Taskにおける注意分配を考慮した拡張肢インタフェースの設計

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Abstract

This thesis focuses on the question of how to design the interface of Supernumerary Robotic Limbs (SRLs) to perform dual tasks efficiently. In our busy daily lives today, the demand for multiple tasks is increasing in order to reduce working time. One solution is to introduce specialized automatic devices for each task (e.g., fully automatic dishwasher, robot vacuum cleaner etc.). However, in the situation of daily life, the items, the environment, and the human intentions are changed from time to time. In these situations, a support method that allows voluntary intervention by humans through some manual operation is required rather than a fully automated response.

Recently, the development of human augmentation technology has contributed to the solution of this problem. In this field, various wearable robotic arms were proposed as additional arms or legs, allowing one human to perform dual tasks. However, while conventional research has given humans the physical means to dual task, performing dual tasking efficiently is very difficult for humans from a cognitive perspective. For example, the most flexible method of manipulating an SRL is through a master slave approach, and some research has attempted to achieve this using the user's foot or head movements as input. However, such a method requires the user to continuously pay a lot of attention to the SRL while manipulating it, which may stop the work done by the natural body arm. On the other hand, some research on the SRL is pursuing an automatic control by measuring human movements and determining assistive actions. This is an approach for humans to pay little attention to the SRL. However, as mentioned above, automatic support by a system is not only unsuitable for the complex environment of daily life, but it also requires the user to pay attention to the robot repeatedly while it is moving automatically, wondering whether it is moving as intended. This can also interrupt the work done by the natural body arm.

Thus, conventional SRL systems do not consider attention problems, making it difficult to achieve high performance in dual tasks. In this thesis, we discussed the design theory of the SRL from the viewpoint of attention allotment in dual tasks, and also presented another challenge: to realize dual tasks at two distant locations (e.g., mixing a pot in the kitchen while opening the front door for a family member who forgot the key). To achieve this, the SRL should not be worn all the time, but

detached from the body as needed to create a situation where the user is as if he or she is present at two points simultaneously (dual-presence situation). Previously, the remote tasks are achieved by telepresence technology, but dual tasks at the remote and current location (dual-presence task) are not achieved. In case of performing dual presence tasks by "detachable" body, it is necessary to pay attention to the remote environment at the same time as the local environment. In addition to the problems of high attention to manipulation and distrust during automatic control, this is one of the factors that reduce the performance of dual tasks

This research aims to develop a new SRL system, Detachable body, which enables us to perform dual presence tasks in daily life, and challenges the research question of how to design a system for high performance dual presence tasks. As an approach to this question, this thesis focused on the cognitive characteristics of humans during dual tasks, and raised the following three issues related to attention allocation, and discussed design theory of Detachable body system through each of them.

(1) Voluntary operation demands a large amount of attention.
(2) Anxiety during automatic operation requires frequent attention.
(3) The processing of environmental information at two points requires a large amount of attention.

The thesis is divided into seven chapters.

In Chapter 1, the effectiveness of human augmentation technology that can perform voluntary physical tasks is discussed from the viewpoint of complexity and fluidity of daily life situations. In addition, the purpose of this thesis is explained by summarizing the difficulty of performing dual tasks efficiently from the viewpoint of human cognitive characteristics, and presenting three issues in the design theory of conventional human augmentation systems.

In Chapter 2, the issue (1) is focused and a semi-automatic intermittent instruction system was proposed that points at an object by the direction of the face and performs an action by voice command, as a voluntary manipulation system that can give instructions with a small amount of attention. The system was implemented in an eyeglass type interface device and enabled pointing with an accuracy of about 1 cm. However, the laser pointer introduced for the purpose of visually indicating the pointing location, improved the accuracy of the instruction but reduced the performance of the task on the natural body. This suggested the design concept that it is better to choose a method that can be manipulated with as small an amount of attention as possible, even if the manipulation involves some error, and that the error can be absorbed by another design element. (e.g., developing a n end effector that can robustly grab the instructed object even if the instruction point is slightly off.)

In Chapter 3, the issue (2) is focused and a feedback (FB) system was proposed that can know the posture information of the Detachable body through somatosensory perception even during automatic operation. The system was implemented in a belt type device using vibrators, and was able to present the position of end effector with an accuracy of about 10 cm. This system can be used in conjunction with an easy calculation task without degrading the performance of the task. In addition, when it is used in conjunction with another slightly more difficult task of measuring hot water, it tends to improve the performance of the task on the natural body by reducing the number of visual confirmations on the Detachable body. This suggested the design concept that when automatic control is included in the operation of the Detachable body, the state of the robotic arm should be transferred by the somatosensory system in order to reduce the anxiety of the Detachable body during the operation.

In Chapter 4, the issue (3) is focused and a dual presence system was proposed that displays two half transparent images of the environment with binocular disparity as a method to clarify the task to which the user is mainly paying attention while having access to environmental information at two points. The system was implemented with a head mounted display and a camera that rotated in sync with the head movement. In the disparity state, the user was able to immediately distinguish between objects in the current location and objects in the remote location with a correct response rate of about 90%. The system was also evaluated in a dual presence task in conjunction with the FB system developed in the previous chapter to provide information about the body at the remote location. The results showed that the performance of the natural body task and the subjective evaluation of usability by NASA TLX were best when there was disparity and FB, when the user was able to focus their attention. This suggested the design concept that it is better to have a clear focus of attention that can be moved and switched freely, rather than a situation where attention is always equally directed to all environments.

In Chapter 5, issues mentioned in Chapters 2 to 4 were discussed again and the contributions and limitations of this thesis were described. As embodied in the three design concepts suggested in the chapters, the design theory of SRLs for working in dual presence tasks to consider the amount of which it deprives people of attention and the amount of which it inhibits or facilitates the switching and distribution of attention when selecting design elements that satisfy the required working functions.

The limitation of this thesis is that it fails to consider the nature of tasks performed with natural bodies and the temporal changes in attention paid to them when examining dual tasks. As another limitation, the extension from dual presence tasks to multi presence tasks, and the scientific implications of using a robotic arm that the user perceives as a body rather than a simple robotic arm for these tasks are expected future research developments.

In Chapter 6, current work progress on the application to the multi presence task which mentioned as a future study was introduced. The effect of increasing the number of tasks on attention allocation through user testing of the multi presence task was discussed, in which the user performs tasks in six locations simultaneously. Finally, Chapter 7 concludes and summarizes this thesis.

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Chapter 1: Introduction

1.1 Background

People living in today's busy society have a need to complete many tasks in a limited amount of time. In particular, there is a large demand for reducing the time spent on household tasks such as cooking and cleaning in daily life, and the market for housekeeping services is expected to grow to 800 billion yen by 2025 [1]. In addition to asking other people to do household tasks like these services, there are other approaches that can contribute to reducing the amount of time spent on daily tasks, for example, automating each task. Many devices have already been developed to automate daily household tasks, such as robot vacuum cleaners [2] and even fully automatic clothes folding machines [3]. On the other hand, the conditions of use of such devices are strictly limited. In order to automate various tasks in daily life, we need to introduce these automatic assisting devices tailored to individual situations, which increases the overall cost. In addition, in the setting of daily life, the correct answers to the assistance change from moment to moment. For example, when grasping the cup, there is a demand to adjust the grasping position and carrying speed depending on whether the cup is filled or not, or when cooking the same dish, there is a demand to change the seasoning mix from the previous time. In such a

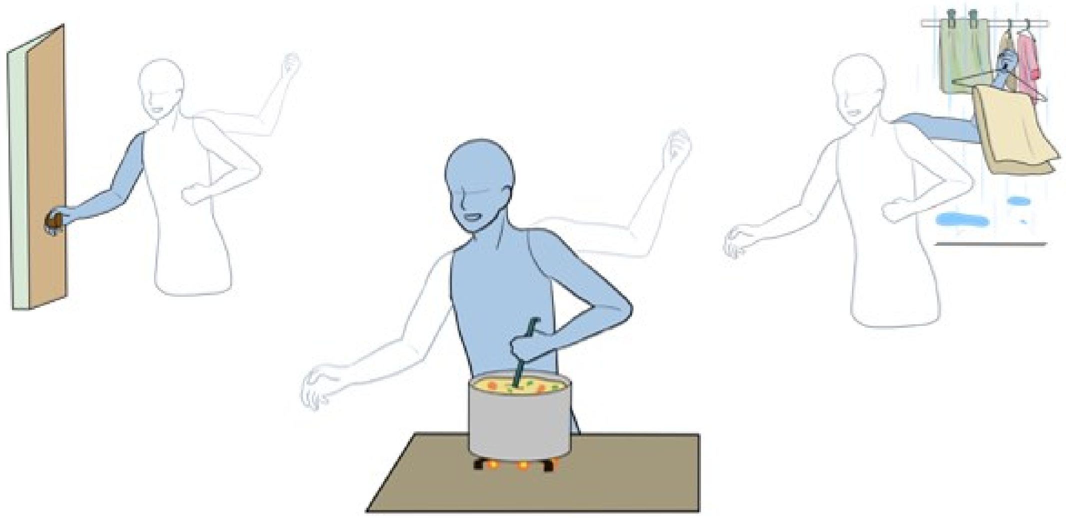


Fig. 1 Dual presence task in daily life

complex environment, it is difficult for a robot to support a task only by autonomous devices, and it is more desirable to have a means of support in which a user can voluntarily intervene according to the situation.

We are considering the use of human augmentation technology [4] [5] [6] [7] to approach task assistance in daily life. In the field of human augmentation technology, we aim to achieve tasks that are physically impossible with the human body (in this thesis, we call this the "natural body" as opposed to the augmented body), and to create new perceptions and sensations. For example, by attaching a robotic arm and handling it at the same time as the natural body, people can have three or four arms, allowing it to perform concurrent tasks such as opening a door with the arm of the augmented body while carrying a large baggage with the arm of the natural body. In addition, the natural human body can only exist in one place and perform a single task (single presence / single task). However, by using this kind of human augmentation technology, it is possible to be in two places at the same time (dual-presence / dual task). For example, stirring a pot on the fire in the kitchen while simultaneously going out on the balcony to take in laundry, as shown in Fig. 1.

Concurrent task refers to the simultaneous progress of two or more task processes. In addition to the value of using human augmentation technology to support concurrent tasks in daily life environments, as mentioned above, it is also valuable from two additional aspects.

One is that the use of an augmented body enables intervention in a variety of physical tasks that occur in daily life environments, and has the potential to provide new work styles and tool development. Concurrent task is already done by everyone in the informational dimension. For example, checking e-mail while attending a meeting, or having a conversation with someone while typing, can be said to be the concurrent task in the sense that two or more tasks are going on at the same time. However, concurrent task with physical works has been difficult to achieve in the past because humans simply did not have the means to do so. For example, it is difficult to hold an umbrella with both arms while using crutches, or to answer the door at the hall while putting a child to bed in the living room, because the number of arms or body parts is limited. In contrast, these physical limitations can be lifted by introducing an augmented body, a physical entity that can be manipulated voluntarily. In addition, until now, humans have only two arms, and there is an affordance [8] that assumes that everyday tasks and the tools used for them are done with two arms. If augmented body allows three or four arms to be used simultaneously for physical tasks, they may not only be able to perform concurrent tasks, but may also be able to increase the convenience and efficiency of work by changing the way each task is performed. This will depend on the level of task performance that we aim for in the design of the augmented body (whether we implement only simple movement functions such as holding and supporting things, or we implement movement functions equivalent to those of the natural body's arms such as writing, or we implement movement functions more advanced than those of the natural body such as positioning to within a few tenths of a millimeter). Either way, there is a possibility of advancing into a completely different lifestyle as a form of physical work.

The other is that by using an augmented body, something that users can feel as their "own body", there is a possibility of providing a new user experience brought about by working with it. The sensation of feeling something as your own body is called "embodiment" [9] [10]. The term of embodiment has many meanings in the field of cognitive science [11] [12]. Ziemke classify embodiment into six types of concepts, ranging from structural coupling between agent and environment to social embodiment [13]. In this thesis, sense of embodiment is defined as "the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body especially in relation to virtual reality applications" [14]. Research on embodiment of augmented body has been conducted in various fields of human augmentation, but there is still no clear answer to the question, "Why do we need to create a "body" instead of just a robot arm or a fully automated system?". There have been several investigations into how embodiment can change human behavior and senses [15] [16]. On the other hand, little has been mentioned about the benefits in performing physical tasks or effect of embodiment to additional body parts which is not existed naturally. However, the difference in the subjective evaluation of whether we feel that we are performing a task with our own body or with a robotic arm as a tool is likely to cause some differences in the way we perform our daily tasks. For example, when you touch an object that you do not want others to touch, such as a baby or an important object, you may be hesitant to perform the task with a ordinary robot arm, but you may be able to perform it if it is perceived as your own body. In other cases, using one's own body to perform a task is thought to be associated with a sense of action ownership, accomplishment, and responsibility. Depending on the presence or absence of these factors, there is a possibility of obtaining a user experience that cannot be obtained when using "ordinary a robot arm/full-automatic system," such as a higher level of satisfaction with the task, or an easier acceptance of errors.

In this way, by incorporating the concept and entity of an augmented body, work in daily life can be developed into a next-generation support that not only improves work efficiency but also expands work styles and creates new user experience. In addition, the number of tasks to be performed by the augmented body and the number of locations where they can be performed are not limited to two. In the future, dual-presence and dual-tasking will be extended to multi-presence and multi-tasking, which will contribute to saving time and improving convenience in daily work by freeing us from the quantitative and locational constraints of the tasks possible for one person, as shown in the Fig. 2. In this thesis, as a first step, we aim to develop an augmented body system that can achieve a "dual-presence task," in which two tasks are performed simultaneously in two locations.

1.2 Application concept

What would an augmented body system capable of dual-presence tasks look like? Until now, most augmented body systems have been designed to be worn on the shoulders or hips [17] [18] [19]. They provide a means for working while in a single-presence situation, but they cannot perform dual-presence tasks. However, unlike

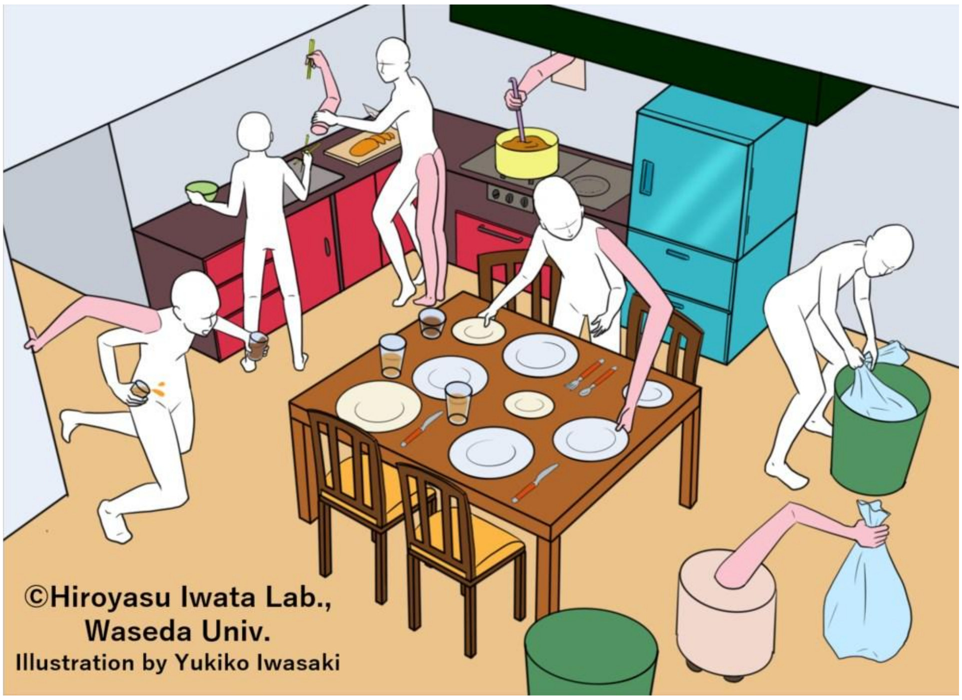
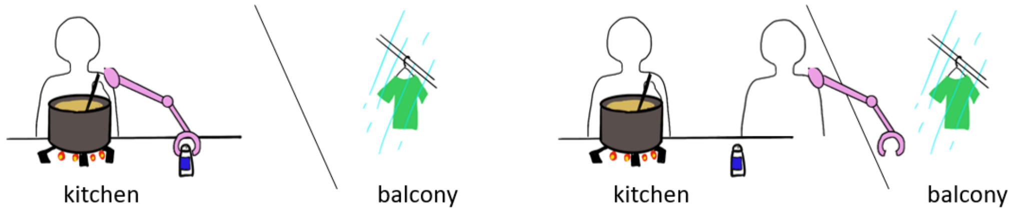
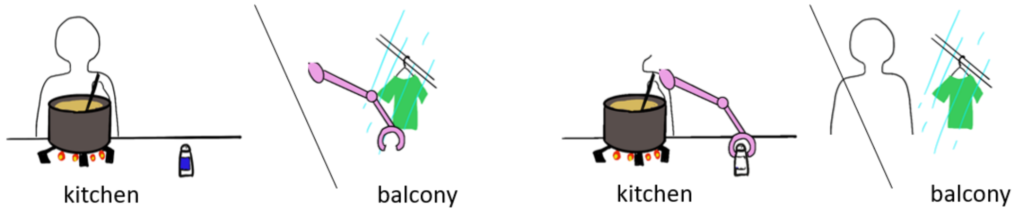


Fig. 2 Scene of daily life with the Extra Limbs



(a) Dual task at two distant places

(b) In case of wearable robot arm



(c) In case of detachable body

Fig. 3 Advantage of Detachable body compared to conventional wearing extra limbs

natural arms, mechanical arms can be detached from the human body. In other words, by allowing the augmented body, which is usually attached to the natural body, to be removed or attached to the environment as needed, dual-presence tasks using the "natural body" and the "detached/attached body" become possible.

Therefore, we propose a "Detachable body" as a new application of augmented body system that can perform dual-presence tasks. Fig. 3(a)-(c) show example of a series of task scenarios using a detachable body. (a) shows a user standing in a kitchen, continuously stirring a pot to prevent it from burning, and using a normal wearable augmented body to get additional seasonings or plates. This is a dual-task situation with a single presence. At this time, if it suddenly rains and user want to go to take in the laundry, you cannot leave in front of the pot. However, by adopting the concept of the detachable body, the augmented body can be detached and placed in the kitchen to allow the user to go to the balcony. If the detached body has mobile function, it also allow the user to stay in front of the pot and they can take in the laundry using the Detachable body. In this way, by placing a part of user's body in a remote location, users can create a situation where they seem to be present in two different locations and work in both locations at the same time (dual-presence task).

Detachable body can realize dual-presence tasks of various situations, depending on where the detached body part is placed: in the environment, on other users, or on oneself [20]. This will be introduced refer to Fig. 2.

1.2.1 Place to the environment

One of the most basic ways to use the Detachable body is to place it in the environment. By placing the Detachable Body at the location where the task is to be performed, the user can perform the dual-presence task at the location where the Detachable Body is placed and at the location where the user's own natural body exists. For example, as shown in the upper center of Fig. 2, the user can stir a pot in front of the stove while serving food at the table. Or it can be placed on a movable object in the environment, as in the right part of Fig. 2. In the figure, the task of going around the room collecting trash from the trash cans is performed by a natural body and a detachable body. In this way, a dual-presence task can be performed even where one task includes the requirement for movement.

1.2.2 Place to the other users

There is a use case for placing the device on another person's body. This can be used to perform a dual-presence task that includes a demand for movement by a third person wearing the device moving around, as in the case of placing it on a moveable object in the environment. Also, it meets a demand for a dual-presence task that includes collaboration with a third person. Another use is to share one's physical skills with others, as shown in the upper left of Fig. 2. In the figure, one user with the skill to handle chopsticks passes his or her detachable body to another person who cannot handle chopsticks well. In this case, for example, if mechanical information such as the position of the chopsticks and the degree of force is stored in the detectable body, the not-skilled person can use it to demonstrate a skill that he or she did not originally have. In this way, by exchanging body parts with others, dual-presence tasks can be achieved that require specific skills for the task.

1.2.3 Place to myself

This is not an example for a dual-presence tasks, but for dual tasks in single-presence. For example, Detachable body that is normally placed on the shoulder and used as an arm, can be used as a foot or finger depending on the task requirements.

In the upper left part of Fig. 2, the user is using the Detachable body normally used as an arm, as a leg by attaching it to the waist, and is cooking while resting the natural leg. As another example, it is usually difficult for us to wash our own back clean when bathing, but by repositioning the arms, this task can be easily accomplished. In this way, by using the concept of separating body parts, we can dynamically reconfigure the conventional body scheme to achieve dual tasks without physical limitations of the body. However, since the output requirements for the system are very different when, for example, lifting a light object as an arm and supporting the body as a leg, such usage may have significant limitations in hardware design.

1.3 Issues and conventional studies

Detachable body is an example of an augmented body application for dual-presence tasks, but there are two major questions to develop it. One is "How can we design a system that can perform dual-presence tasks?". The other is "How can we design a system that feels like our body when we wear it or detach it?". In the former, the goal is to achieve a dual-presence task, which requires, for example, that the task be performed as the user intends, and that the work time be reduced by performing two tasks simultaneously rather than one at a time. In the latter case, the goal is to establish the feeling of "embodiment", which requires, for example, that the user subjectively feels the object as if it were his or her own body, and that there is reaction or behavioral change, such as reflexively retracting an augmented body in response to an unpleasant stimulus, just as in a natural body. These two questions are unsolved problems, and sometime it may be difficult to satisfy them simultaneously. Depending on the system design, the design elements for the dual-presence task and the design elements for the embodiment may repel each other. For example, it is said that synchronization of tactile stimuli is effective in the natural body as a condition to induce embodiment in the object [21] [22]. However, the performance of the dual-presence task may be reduced due to confusion over which is which in the tactile stimuli returned from the natural body and the Detachable body. In addition, there is the question of why it is necessary to feel the robot arm as one's own "body" in the first place. Therefore, in this thesis, we will focus on the former question of how can we design a system that can perform dual-presence tasks.

There are two major hurdles to developing a system capable of dual-presence tasks. One is to make dual-tasking possible, and the other is to do it in dual-presence situations. In the conventional studies, various augmented body systems have been proposed for performing tasks while working, in which a robotic arm is attached to the shoulder or waist and used as an additional arm or leg [17] [19]. These robotic arm which is used as human’s additional limbs called “Supernumerary Robotic Limbs [23],” hereinafter reffered to as SRL. On the other hand, handling a SRL at the same time as one's own body is a dual-task for humans, which is considered to be difficult due to human cognitive characteristics [24] [25] [26] [27] [28]. In addition, various studies and systems have been proposed for performing tasks at distant locations, such as immersing oneself in a robot at the remote place or an avatar in the virtual world [29] [30] [31] [32] [33]. On the other hand, few systems have been proposed for working in such remote locations while simultaneously continuing to work in the current location, and it is unclear what design elements should be considered in order to maintain work efficiency of two tasks and increase subjective work satisfaction. In this section, the discussion on these two hurdles will help to clear the problem setting to be approached in this thesis.

1.3.1 Challenge for dual task

Attempts to use a wearable robot arm to perform dual tasks have been made in

Fig. 4 Enhancing Stroke Generation and Expressivity in Robotic Drummers

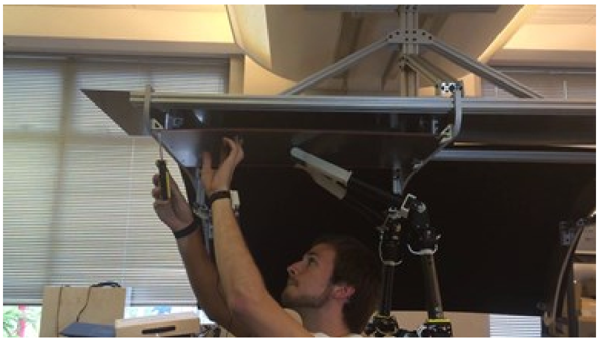


Fig. 5 Supernumerary robotic limbs for installing ceiling panel

the field of human augmentation, especially in the development of SRLs. For example, applications such as beating a drum with three arms [34] (see Fig. 4), or supporting a large ceiling board with two of its four arms while fastening screws with the other two arms [17] (see Fig. 5), have been proposed. In many of these applications, the robot is studying and adopting algorithms to read the current work situation and act autonomously within a certain work sequence. This means that even if the human completely focused on his own movements, the SRL system can autonomously judge the situation and act as it should. On the other hand, as described in Section 1.1, our application is aim to apply for everyday life situations, and we assume that the user can voluntarily manipulate the SRL in order to respond to various and flexible environmental factors and the operator's intentions. There are several examples of such voluntary manipulation method in the past SRL applications. For example, a technology to measure the myoelectric potential in the chest and control the SRL according to the change in the potential [35], and a technology to control the SRL by using the left and right feet like joysticks [19], have been proposed. However, these manipulation are conducted under a dual-task situation of manipulating the extended body and the natural body, and humans are cognitively poor at performing this dual task [24] [25] [36]. Since the purpose of dual-task using SRL is to shorten work time and improve convenience by performing two tasks at once, it is meaningless if trying to perform two tasks at once in the end reduces work efficiency rather than when performed them sequentially. Therefore, a manipulation method for the SRL must be designed from the perspective of how to make this dual task feasible. However, there has been no discussion on "the design of SRLs that takes into account human cognitive characteristics and does not reduce the work efficiency of dual-tasking with voluntary manipulation.

There are several reasons why multitasking does not work well as a human cognitive structure. The ability to multitasking is innately determined to some extent, and it is believed that only about 2% of the population is capable of performing two tasks completely simultaneously [37] [38]. The reasons why it is difficult for the remaining 98% have been discussed in various ways, but in this thesis we focus on two of the major ones: the limitation on attentional resources, and the cost of task switching, which will be discussed in detail below.

1.3.1.1 Limitation of attentional resources

The first is the inability to handle several tasks simultaneously due to limited attentional resources [39] [40] [41]. Attention is described as a kind of concentration and focusing of consciousness, but it has not been clearly defined or quantitatively evaluated [42] [43]. On the other hand, attention is said to be severely limited in terms of time and capacity [44]. Therefore, as shown in Fig. 6, as a result of allocating the amount of attention necessary to carry out task 1, the situation occurs where the amount of attention necessary to carry out task 2 cannot be sufficiently secured. There are several models of limitation of attention resources. General resource capacity model is that there is one common pool of attentional resource [45]. On the other hand, multiple resource theory is that there are several pools of attentional resources [46]. Some study indicates that the consumption of attentional resources can be reduced by using several different modalities [47]. In any case, these theories and models have in common that there are some limitation to human attention. For example, an accident involving a careless driver is caused when the driver's attention is diverted to something that appears along the road, and as a result, the driver's attention to driving is reduced and he or she is unable to deal with the abnormal situation that occurs there.

The same situation can be expected when using the SRL. As mentioned above, the

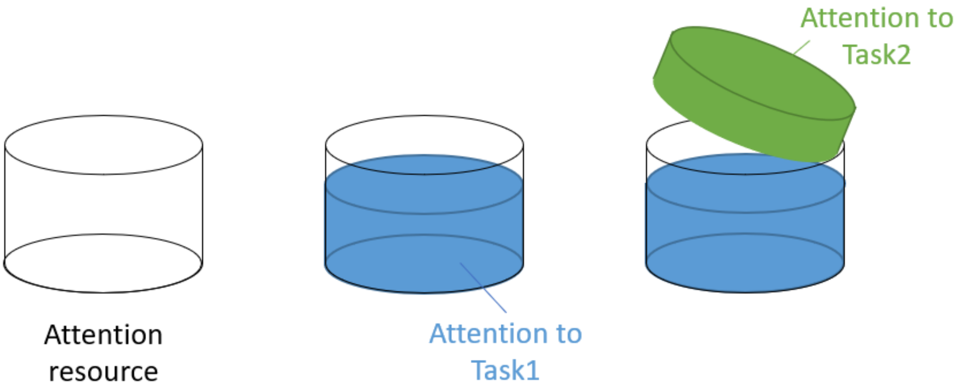


Fig. 6 Model of attention resource limitation

master-slave method, which allows for more freedom of movement, is more suitable than the fully automatic operation method for supporting tasks in complex environments such as daily life environments. However, as shown in Fig. 7, the master-slave method requires the user to pay continuous attention to the SRL throughout the operation, which consumes attentional resources and interrupts the control of the natural body and the task being performed by it. This is the first issue that we will address in this paper.

- [Issue 1]: In a fully manual operation that emphasizes voluntariness, a large amount of attention is taken to the SRL, making it difficult to efficient dual-presence task.

To solve this problem, a semi-automatic manipulation method is considered to be effective. Because it does not leave everything to the judgment of the system as in the case of fully automatic manipulation, but allows intermittent intervention as needed and does not require as much continuous attention as fully manual manipulation. In this case, it is difficult to set a criterion for how much the amount of attention required for the manipulation of the SRL should be reduced. Because the amount of attentional resources required by the task on the natural body side depends on the nature of the task. For example, it is possible that a monotonous and repetitive action such as stirring a pot does not consume much attentional resources. On the other hand, dangerous task such as cutting vegetables with a knife may consume large attentional resources. However, in any case, designing the SRL

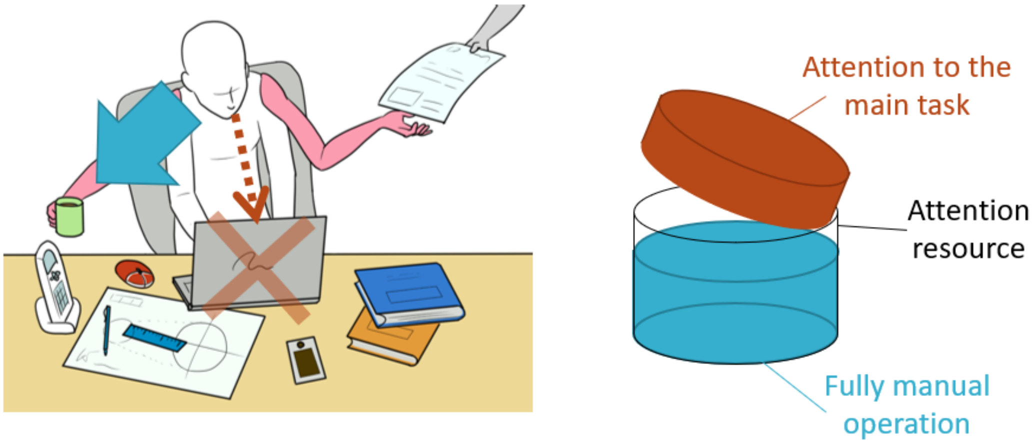


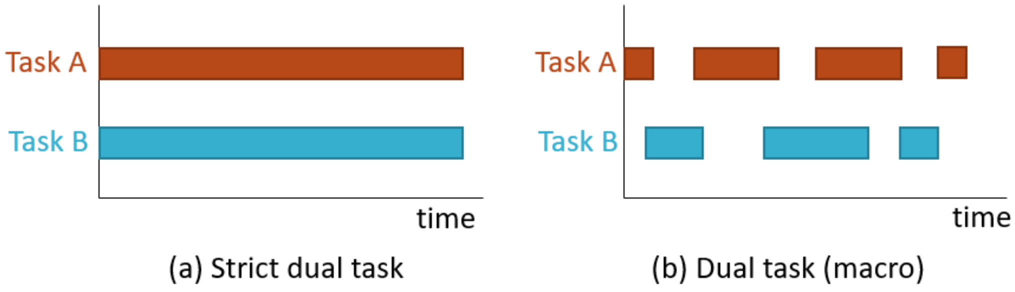
Fig. 7 Overflow of attention resource when fully manual operate the SRLs

system so that the attentional resources required to use it are as small as possible will make it easier to perform dual tasks with the natural body task in a wider range of situations.

1.3.1.2 Cost of task switching

The second is that performance is degraded due to switching costs when tasks are switched. Strictly speaking, dual-tasking is the process of performing two tasks completely simultaneously. However, in reality, as shown in Fig. 9, there are many cases in which humans are switching between two tasks in detail, and the task satisfies this requirement as a whole, the term "dual task" is often used in a broad sense that includes these two cases as well [48]. In this thesis, we use the term "dual task" in a broad sense because the latter type of work involving task switching is more realistic for many people. As shown in Fig. 8, it is known that when task switching occurs, the performance degrades [49]. This is called the switching cost [50] [51] [52] [53]. This occurs every time a task is switched. In other words, the more frequent the task switching is, the worse the performance becomes. For example, if you are driving and have to visually check the speed meter every three seconds, it is easy to imagine that you cannot concentrate on the road in front of you at all.

When using the SRL, in addition to switching that is unavoidable due to the task content of dual-tasking, there is also unnecessary switching that occurs due to the design and usability of the system. For example, if an error occurs while the SRL is operating, such as bumping into a surrounding object or person or failing to operate as instructed, it is expected that attention will be repeatedly directed toward the SRL due to the correction or anxiety about the next error. Particularly, as discussed in the previous section, when partial automation is incorporated into the operation of SRL to avoid continuous consumption of attentional resources by fully manual operation, the user cannot be aware of the state of the robot arm during the operation.



(a) Strict dual task (b) Dual task (macro)

Fig. 8 Concept of "dual task" in this thesis

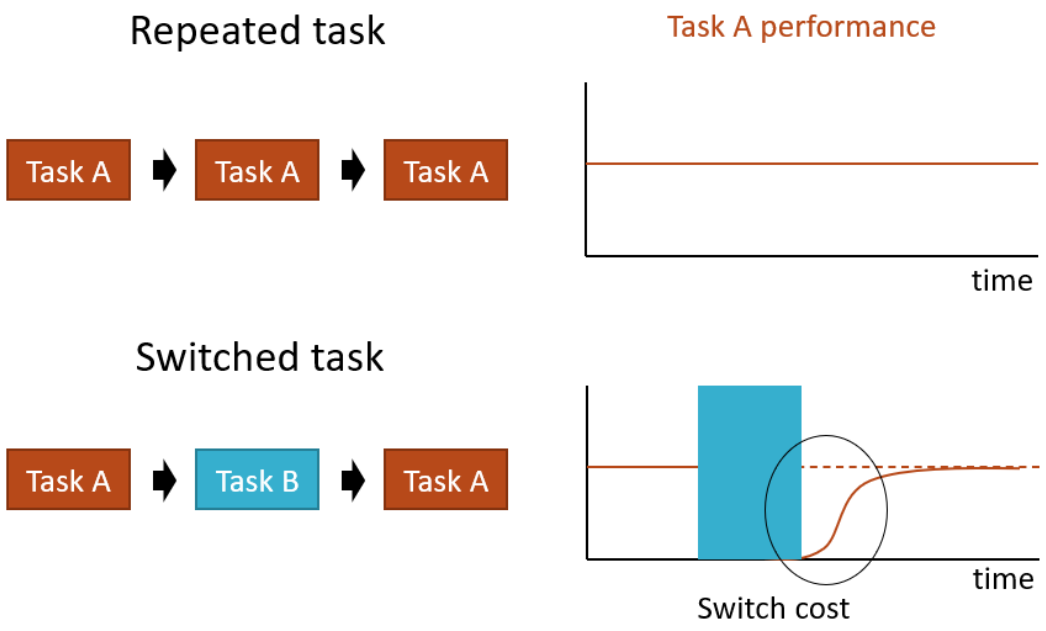


Fig. 9 Model of switching cost

Therefore, the second issue we will address in this thesis is as follows.

- [Issue 2]: The feeling of anxiety about the state of the SRL, such as in automated parts, causes user to pay attention to it repeatedly, making it difficult to perform efficient dual-presence task.

As an approach to this problem, if we have the same somatosensation or tactile perceptions as the natural body, we can confirm its situation without having to check the state of the SRL with our eyes every time. In the natural body, it has proprioception that allow us to know the position and posture of each body parts [54]. For example, in the case of serving dishes, we can safely place a plate on the desk by turning our attention to it only when we feel the SRL approaching the desk. This eliminates the need to check repeatedly that the plate will not hit the desk. In this way, by designing the task so that the number of switches to the task on the extended body side are kept as small as possible while maintaining the degree of freedom of semi-automatic intervention, dual tasks with the task on the natural body side can be easily established.

1.3.2 Challenge for dual presence

The concept of dual-presence or multi-presence itself has been proposed in discussions of presence [55] [56]. Presence is the feeling of being there, and multi-presence is the feeling that a person exists in and has access to multiple locations simultaneously, including the virtual and physical worlds [57]. This has been discussed from various aspects, from the practical example of being able to start up two online meetings at the same time and communicate as if you were in two places at the same time, to the scientific question of whether or not humans can really gain a new sense of being in two environments at the same time [58]. In addition, several applications have been proposed that challenge the creation of such a state in practice. For example, a system has been proposed that allows users to feel as if they are communicating with two people at the same time by superimposing two screens through each other (Fig. 10 [59]). In addition, some teleoperation robots have been designed to be used several ones simultaneously by one person, thus realizing a pseudo-multi-presence [60]. However, most of these studies have focused on communication, and there has been little discussion of the development of systems that perform physical tasks in a dual-presence state, or of the design elements of systems that are involved in task performance in such a state. For example, many tele-operated avatars are designed to achieve a high level of immersion by wearing a head-mounted display and to completely synchronize one's view with that of the remote avatar [61] [62]. However, such fully immersive systems make it difficult to

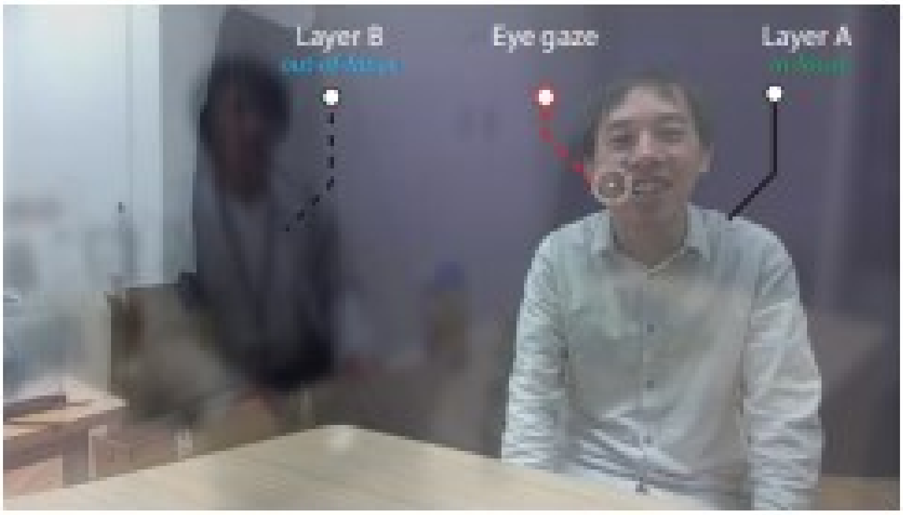


Fig. 10 Layered telepresence system [59]

perform physical tasks simultaneously in the current location.

The concept of Detachable body can provide a physical means of dual-presence tasking. On the other hand, the validity of such a work style should be judged from the improvement of task performance and time efficiency, which inherits the problem of cognitive difficulties of dual tasking as mentioned earlier. Additionally, when dual-tasking with dual-presence, a further problem related to attention arises. This is the problem of how to present the environmental information at the remote place, and how to make it be processed simultaneously with the information at the current place. For example, when we consider the task of taking in laundry on the balcony using a Detachable body while we are in the kitchen, we cannot see the balcony from the kitchen, nor can we feel the intensity of the rain from the sound or touch. Therefore, it is necessary to present the environment of the balcony to the natural body in some way. In this case, in addition to the task of manipulating the SRL, the user is required to acquire visual, tactile, and auditory information about the environment where is completely different from current one, and to process this information while switching between the two at the same time or at any given moment. This increase in the amount of information should be processed, consume more attentional resources required when handling the detached body. As a result, it also increases the possibility that attention will be switched to the task of the detached body side at unneeded times. Therefore, we assume that the third issue that we will address in this thesis is as follows.

- [Issue 3]: Dual-presence increases the amount of environmental information that needs to be processed, which takes up a large amount of attention and makes it difficult to perform efficient dual-presence task.

As described above, the major challenge in realizing a dual-presence task with a Detachable body lies mainly in the limitations and characteristics of human cognitive processing of the task. However, in the field of human augmentation, there is no system designed from the viewpoint of the feasibility of such a task and the analysis of human's attentional characteristics. For this reason, it is necessary to clarify the design theory of how to handle the design elements related to human attention allocation in a dual-presence task from the above three issue settings.

1.4 Research purpose and approach

The final goal of this study is to develop a manipulatable SRL system that can perform dual-presence tasks in order to support various tasks in daily life. We proposed a new concept of an SRL called the Detachable body as an application to achieve this, and showed the following three issues that are of concern from the viewpoint of human's attention allotment in performing dual-presence tasks.

(1) In a fully manual operation that emphasizes voluntariness, a large amount of attention is taken to the SRL, making it difficult to efficient dual-presence task.

(2) The feeling of anxiety about the state of the SRL, such as in automated parts, causes user to pay attention to it repeatedly, making it difficult to perform efficient dual-presence task.

(3) Dual-presence increases the amount of environmental information that needs to be processed, which takes up a large amount of attention and makes it difficult to perform efficient dual-presence task.

The above three problems can be discussed through the interface design of the SRL system, as shown in Fig. 11. For example, (1) is discussed through the design of an operation system because it is a problem related to the operation method. (2) is

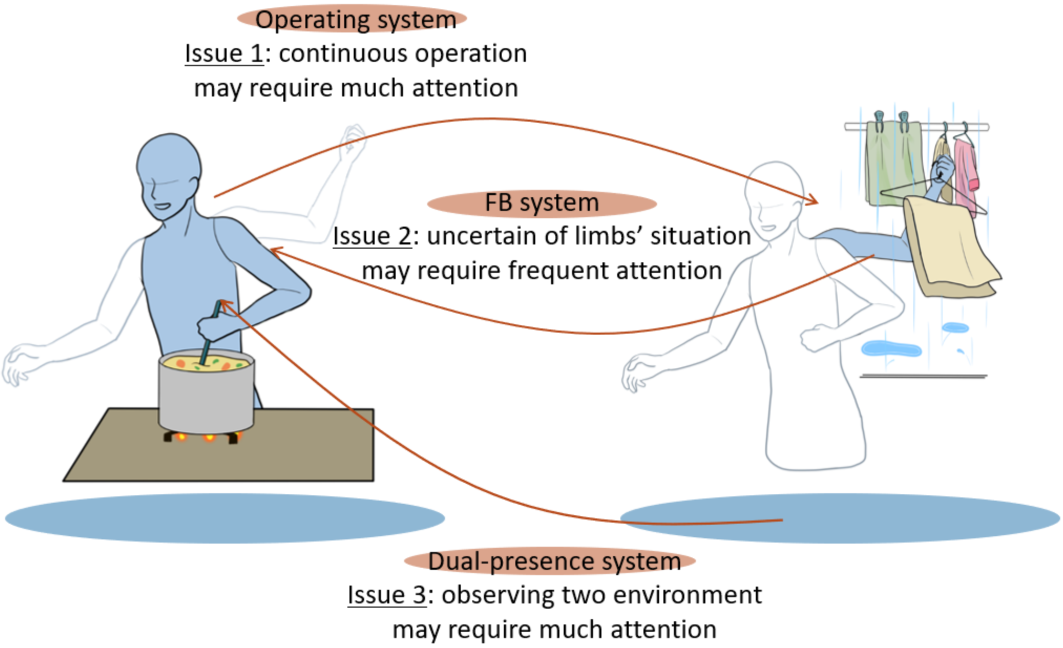


Fig. 11 Issues and interface elements

discussed through the design of a FB (feedback) system because it is a problem related to the state recognition of the SRL. (3) is discussed through the design of a dual-presence system because it is a problem related to the information processing when the user exists in two environments simultaneously.

In the next and subsequent chapters, we will approach each issue through prototyping these three interface systems and evaluating their effect on performance of the dual-presence task, to discuss the question of how can we design a system that can perform dual-presence tasks. This is a new design theory of the SRL offered from the aspect of human cognitive characteristics in dual tasks.

1.5 Structure of the thesis

The structure of this paper is as follows. The relationship between the contents of the chapters and the publications is shown in Fig. 12.

- In Chapter 1, the effectiveness of human augmentation technology that can perform voluntary physical tasks is discussed from the viewpoint of complexity and fluidity of daily life situations. In addition, the purpose of this thesis is explained by summarizing the difficulty of performing dual tasks efficiently from the viewpoint of human cognitive characteristics, and presenting three issues in the design theory of conventional human augmentation systems.
- In Chapter 2, the issue (1) is focused and a semi-automatic intermittent instruction system was proposed that points at an object by the direction of the face and performs an action by voice command, as a voluntary operation system that can give instructions with a small amount of attention. The system was implemented in an eyeglass type interface device and enabled pointing with an accuracy of about 1 cm. However, the laser pointer introduced for the purpose of visually indicating the pointing location, improved the accuracy of the instruction but reduced the performance of the task on the natural body. This suggested the design concept that it is better to choose a method that can be manipulated with as small an amount of attention as possible, even if the operation involves some error, and that the error can be absorbed by another design element. (e.g., developing a n end effector that can robustly grab the instructed object even if the instruction point is slightly off.)

- In Chapter 3, the issue (2) is focused and a feedback (FB) system was proposed that can know the posture information of the Detachable body through somatosensory perception even during automatic operation. The system was implemented in a belt type device using vibrators, and was able to present the position of end effector with an accuracy of about 10 cm. This system can be used in conjunction with an easy calculation task without degrading the performance of the task. In addition, when it is used in conjunction with another slightly more difficult task of measuring hot water, it tends to improve the performance of the task on the natural body by reducing the number of visual confirmations on the Detachable body. This suggested the design concept that when automatic control is included in the operation of the Detachable body, the state of the robotic arm should be transferred by the somatosensory system in order to reduce the anxiety of the Detachable body during the operation.
- In Chapter 4, the issue (3) is focused and a dual presence system was proposed that displays two half transparent images of the environment with binocular disparity as a method to clarify the task to which the user is mainly paying attention while having access to environmental information at two points. The system was implemented with a head mounted display and a camera that rotated in sync with the head movement. In the with disparity state, the user was able to immediately distinguish between objects in the current location and objects in the remote location with a correct response rate of about 90%. The system was also evaluated in a dual presence task in conjunction with the FB system developed in the previous chapter to provide information about the body at the remote location. The results showed that the performance of the natural body task and the subjective evaluation of usability by NASA TLX were best when there was disparity and FB, when the user was able to focus their attention. This suggested the design concept that it is better to have a clear focus of attention that can be moved and switched freely, rather than a situation where attention is always equally directed to all environments.
- In Chapter 5, issues mentioned in Chapters 2 to 4 were discussed again and the contributions and limitations of this thesis were described. As embodied in the three design concepts suggested in the chapters, the design theory of SRLs for working in dual presence tasks to consider the amount of which it deprives people of attention and the amount of which it inhibits or facilitates the switching and distribution of attention when selecting design elements

that satisfy the required working functions. The limitation of this thesis is that it fails to consider the nature of tasks performed with natural bodies and the temporal changes in attention paid to them when examining dual tasks. As another limitation, the extension from dual presence tasks to multi presence tasks, and the scientific implications of using a robotic arm that the user perceives as a body rather than a simple robotic arm for these tasks are expected future research developments.

- In Chapter 6, current work progress on the application to the multi presence task which mentioned as a future study was introduced. The effect of increasing the number of tasks on attention allocation through user testing of the multi presence task was discussed, in which the user performs tasks in six locations simultaneously. Finally, Chapter 7 concludes and summarizes this thesis.

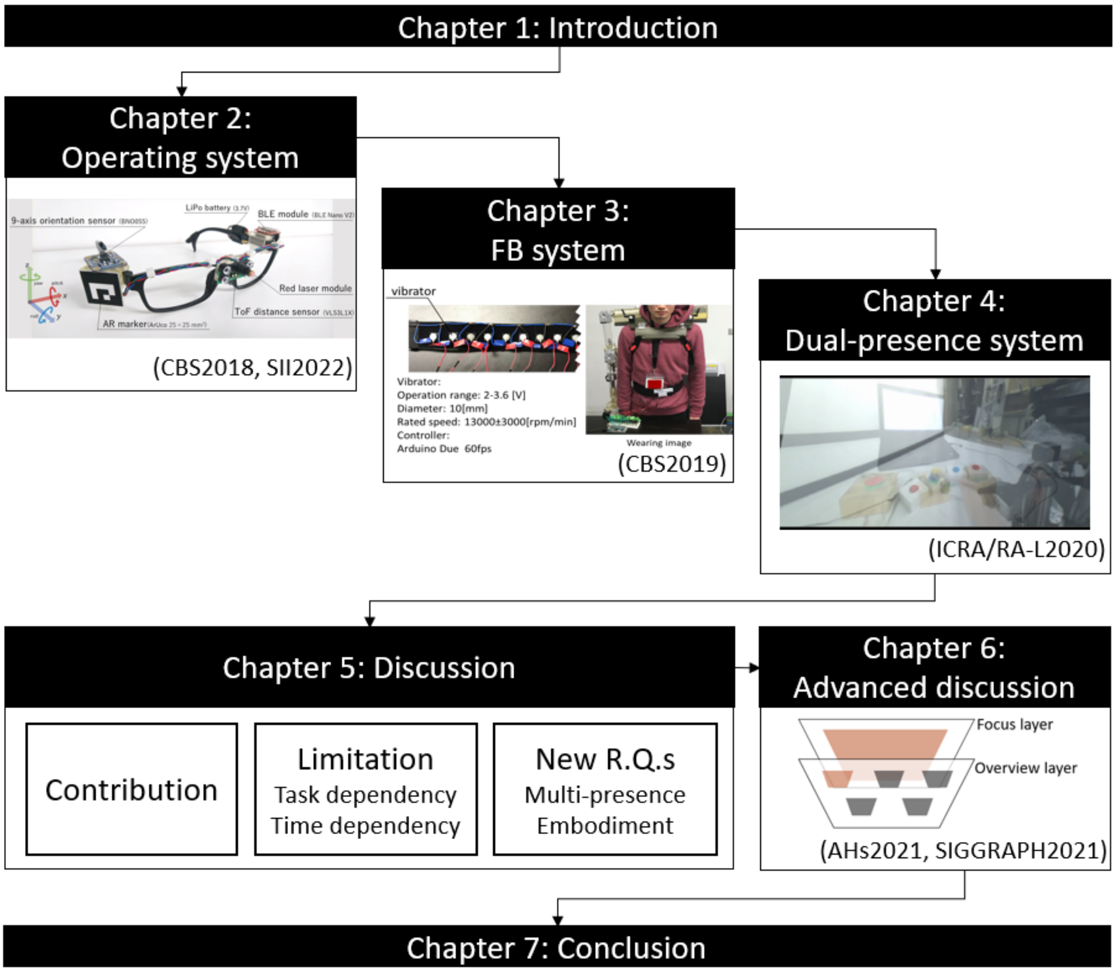


Fig. 12 Structure of the thesis and relative publications

Chapter 2: Operation System

In this chapter, we will address issue (1), "In a fully manual operation that emphasizes voluntariness, a large amount of attention is taken to the SRL, making it difficult to efficient dual-presence task". We will discuss the design elements of the SRL system for efficient concurrent task by designing an operation system for the SRL and evaluating its usability in a dual-task experiment.

2.1 Issue and approach

Conventional operation of the SRL has been either fully manual or fully automatic. Fully manual operation is a method that uses a mechanism such as a joystick or keypad to continuously control the end effector position of the SRL. These are often reproduced by using modalities other than the hands as input, for example by using the feet or the head tilt as a joystick [19] [63]. In fully manual operation, any motion trajectory, such as mixing, picking up an object, or gesturing to a person, can be directed arbitrarily. However, it requires continuous attention to the operation, which consumes attentional resources for a long time. On the other hand, a fully automatic method is one in which the system analyzes the current work state and automatically executes the next necessary action based on the work image captured by the camera or the encoder information of the joint angles of the SRL [64]. For example, a classifier called the Colored Petri Net (CPN) is used to classify the work of assembling parts of an airplane and automatically determine the work to be done [65]. In other study, the opening and closing of extra fingers is automatically performed by judging the opening and closing state of the user's hand [66]. In this fully automatic operation, the human does not need to give explicit commands, such as tilting the stick or making voice commands, so the desired action can be accomplished with little consumption of attentional resources. However, this method has a narrow range of application, because it is difficult to respond to changes in the process. In summary, in order to achieve the objective of this study, which is to support daily life, a fully manual system is likely to consume too much attentional resources and prevent the performance of the task, while a fully automatic system is likely to specify the usage situation in advance and it is not suitable for supporting complex tasks which is required in daily life environment.

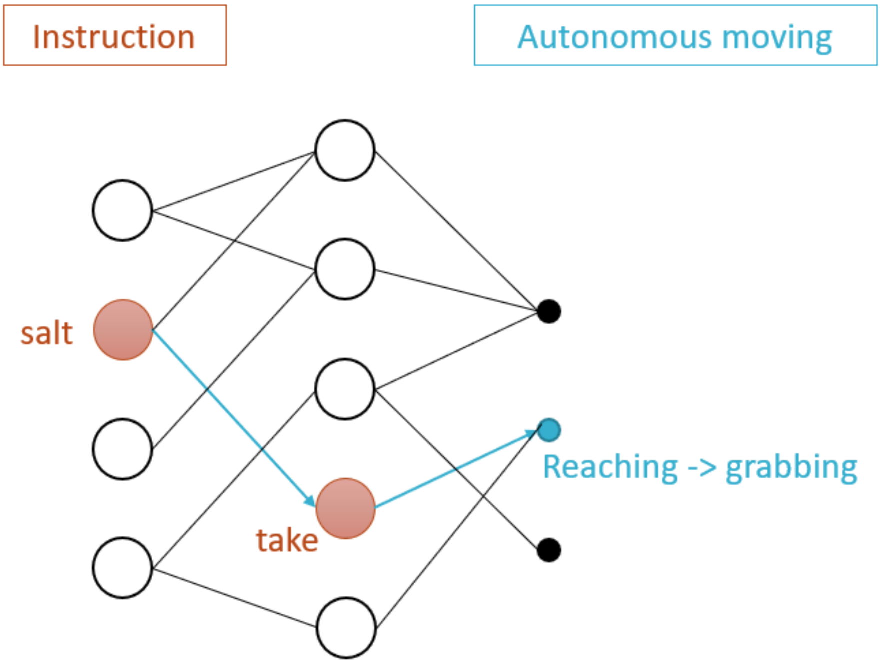


Fig. 13 Semi-autonomous control of the SRLs

Therefore, we focus on semi-automatic operations as a way to reduce the consumption of attentional resources without significantly impairing the diversity of movement and instructions. Conventionally, an index that divides the automation level into 10 levels has been presented as a concept to express the form of cooperation between humans and machines [67] [68]. This is an index of automation related to decision making. The semi-automatic operation in this thesis means that the human makes the decision, but the system performs the "automatic action" based on the decision. In this case, as shown in Fig. 13, only the necessary nodes in the work sequence are specified manually, and the routine part of the operation is executed automatically. For example, when we reach out to pick up a cup, we pay attention to the location of the cup, but we pay little attention to the rotation angle of the elbow and shoulder joints to reach the cup. In the operation of the SRL, for example, only the coordinates of the point where the cup is located and a voice command such as "pick it up" are input manually, and the process of reaching and grasping the specified coordinates is done automatically. We can reduce the attentional resources required for operation only at the moment of specifying the "object" and "action" while maintaining the freedom of selecting the object or action. In this thesis, we use the term "intermittent instruction" to define this method of instruction that directs the necessary attention only at the necessary moment, as opposed to the conventional "continuous instruction" such as master-slave operation.

Since intermittent instructions include some aspects of automation, such as the part of reaching for an object as mentioned earlier, it is necessary to set the required actions of the SRL with some restrictions compared to a fully manual method. According to the International Classification of Functionality in Human Activities [69] [70], which classifies activities performed in daily life, the most frequent activities performed by humans in daily life are picking up and holding objects, followed by placing objects, which account for about 70% of all activities performed in daily life. As mentioned above, these operations can be achieved by specifying a target object or a target point and pre-programmed motion sequences (e.g., reaching and grasping for acquisition and holding, and reaching and releasing for installation) [71]. Therefore, the operation systems were designed with these functions of acquisition, holding, and installation actions by specifying the target object and the action.

In order to specify the object and the action, there is a possibility to utilize various modalities. Since these modalities are used in a dual task with the natural body, we cannot use our two arms for this method (e.g., operating a joystick with the hands, gesturing with the hands, etc.) that is mainly used in the task on the natural body side. As hands-free modalities, various options are possible, such as voice, EEG, EMG, gaze, etc. [72] [73] [35] [74] [75]. There have also been attempts to operate the SRL using electrical signals from the brain [76]. Considering the simplicity and flexibility of the devices used to acquire signals in everyday life, voice commands are a very intuitive modality. For example, when a user input "pick up the plate" by voice command, and from the word "plate," the location of the plate in the environment can be identified by image recognition, and used as the input coordinates of the target. However, the problem with voice instructions is that they require a lot of pre-learning. For example, in order for the system to recognize a small bowl that was just bought yesterday as a "plate," it is necessary to learn the image of the plate and its label in advance. This process significantly narrows down the adaptable situations, as was the problem during full automation. In addition, when combining this with other features, such as "blue plate," the system is able to specify an object to some extent without prior learning based on multiple factors, but it is difficult for the system to determine "how blue" when there are light blue plates, cobalt blue plates, deep blue plates, and dark blue plates in the environment. As a result, the system ends up repeating the instructions with different expressions, thus losing the

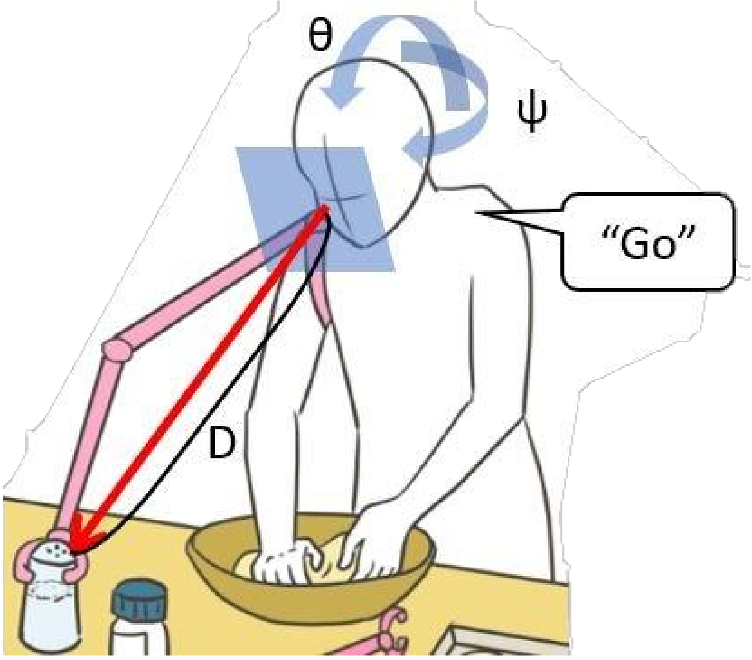


Fig. 14 Point instruction by a "face vector"

advantage of intermittent instruction, which is the reduction of attention time. Therefore, it is better to specify the target object or target point by direct physical pointing, we chose face orientation (face vector) as the modality for this purpose. As shown in Fig. 14, a pointer is fired from the center of the face in the direction of the vertical direction, and the target object is pointed by adjusting the direction of the face. We chose to use the face orientation for pointing to avoid temporal overlap of modalities, since vision is frequently used in the execution of natural body tasks. For motion input, we decided to use voice input since there are only three commands ("take it," "put it," and "hold it"). In summary, the approach to problem (1) is to make the attention directed to the SRL intermittent during operation by limiting the input only "target point" and "action" with pointing to the three-dimensional coordinates of objects by a face vector and with making voice command.

2.2 Prototype development

In order to reduce the attentional resources required for operation while maintaining the degree of freedom of the target action, we take an approach of intermittent control in which the target point is specified by the face vector and the

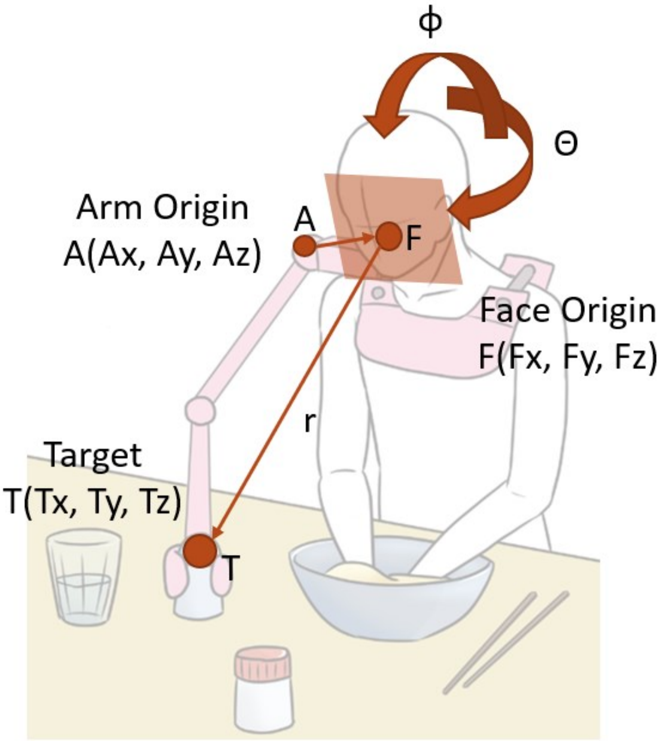


Fig. 15 Variables for calculating the target point from face vector

action sequence is specified by the voice. In this paper, we describe the development of an operation system prototype that satisfies the above functions.

The coordinates of the target point, which is pointed by the face vector, are calculated as follows: the origin of the robot arm, the center point of the face, and the target coordinates are set as shown in Fig. 15. In the coordinate system with the user's face center point as the origin, the target point is obtained in polar coordinates using the face angles Θ and φ and the distance r from the face to the target point. In order to convert this into a coordinate system centered on the robot arm for its operation, the positional relationship of the user's face center point with respect to the robot arm can be obtained and subtracted, and the final derivation equation is as follows.

$$\overrightarrow{AT} = \overrightarrow{AF} + \overrightarrow{FT} = \begin{pmatrix} Fx - Ax \\ Fy - Ay \\ Fz - Az \end{pmatrix} + \begin{pmatrix} r\cos\theta\sin\varphi \\ r\sin(-\theta) \\ r\cos\theta\cos\varphi \end{pmatrix} \quad (1)$$

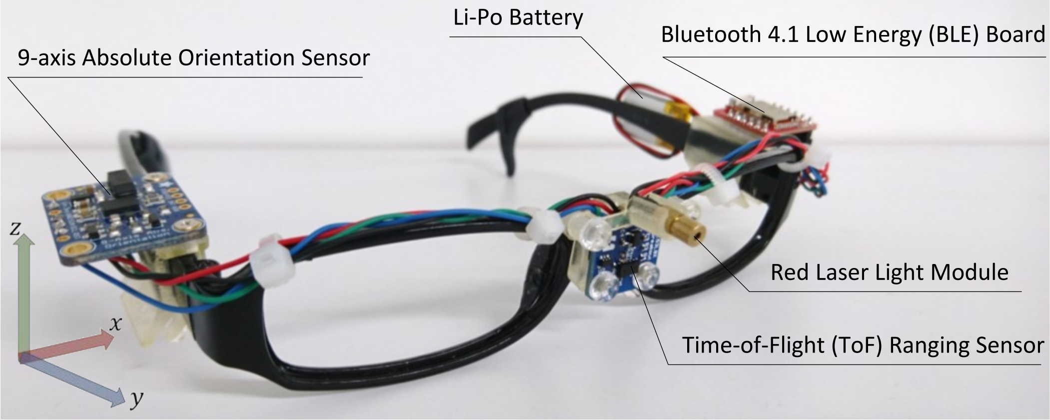


Fig. 16 Prototype of eye-glass type interface for a face vector

In order for the robot arm to know the position of the target object in its own coordinate system using these equations, it requires some values. The distance between the user's face and the target is obtained by the distance sensor. The orientation of the user's face is obtained by the IMU sensor. We can also obtain the position of the user's face relative to the robot arm, for example, by attaching an AR marker to the user's face and capturing it with a camera fixed to the robot arm,

In order to obtain these values, it is necessary to attach an IMU sensor to the head to obtain the face orientation and a distance sensor to obtain the distance to the target. As a hardware base, some accessories such as hats, glasses, and masks are considered that have been conventionally used near the human face. In this study, we used eyeglasses as a hardware base because it is easy to install the distance sensor between the eyes, which is the center of the face. Fig. 16 shows the appearance of the developed eyeglass-type device. The total weight is 34g, the processing frequency is 200Hz, and the data is transmitted to a PC by a BLE module (BLE Nano v2; RedBear, America). In this interface, sensing modules are attached to the frame with 3D printed parts (Object500 CONNEX; Stratasys, America). A 9-axis absolute orientation sensor (BNO055; Bosch, Germany) is fixed to the temple of the glasses to measure the orientation of the face. The distance from the target was obtained from a ToF infrared laser sensor (VL53L0X; ST Microelectronics, Switzerland)..

The developed instruction interface using face vectors aims to achieve intermittent control by only pointing at a target point and making movement commands. However, unfamiliarity with pointing by face orientation may create new cognitive challenges. For example, the user may think that they are pointing their face toward the plate they want to pick up, but in reality they may be pointing at a slightly different point. If they continue to give instructions such as "pick it up," a task error will occur, and this repeated correction will increase the attentional resources required for the operation, thus losing the benefit of intermittent control. To prevent this from happening, we implemented a visual biofeedback (vBF) function in which a red laser pointer is placed just above the distance sensor of the eyeglass interface and illuminated in the direction of the face vector to visually indicate the point where the user is currently instructing. The red laser pointer used is a Class 1 laser, which is considered safe even if the naked eye looks directly at it for 100 seconds. We expected that this visualization function would make pointing with face vectors more accurate and reduce the consumption of attentional resources by reducing errors.

In the next section, we will use the developed interface prototype to verify the effectiveness of this intermittent control and the usability of the interface in a two-step procedure. First, we investigate whether "intermittent instructions" are effective for dual-tasking in comparison to conventional "continuous instruction". Using only the IMU sensor in the interface prototype, we implement a continuous instruction mode in which the hand position is controlled completely manually by head tilt. Next, we investigate whether visualization improves pointing accuracy and how it affects dual-task performance when using this interface as an intermittent instruction to point a target point by face vector.

2.3 Evaluation: effect of point instruction

In this section, we investigate whether intermittent or continuous instructions are more suitable as a method of operating SRLs. Both types of instruction mode can be implemented in the developed interface. In this section, we refer to intermittent instructions as "point instructions" and continuous instructions as "path instructions".

In path instruction, the SRL is moved by tilting the head in the direction of each of the three degrees of freedom along which the head can be moved: yaw, pitch, and roll (see Fig. 17). In this example, the roll rotation corresponds to the x-axis (horizontal), the pitch rotation to the y-axis (vertical), and the yaw rotation to the z-axis (depth). In order to convert the sensed value into the amount of movement of the robot arm, Gompertz function was used, in which amount of movement varies depending on the magnitude of the tilt [77].

In this section, we operate the SRL using the point-instructed and path-instructed methods and verify the difficulty of performing dual tasks. The dual task in this

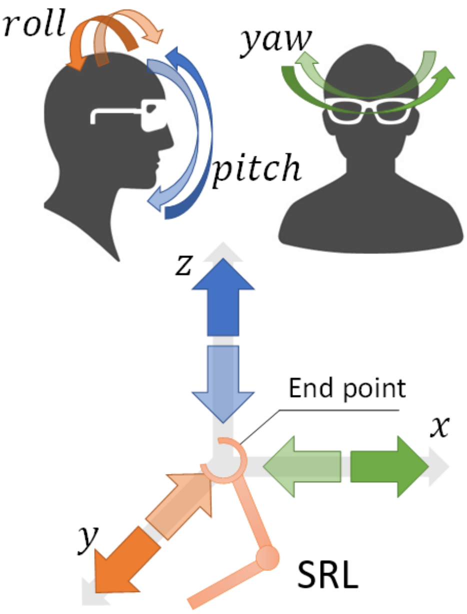
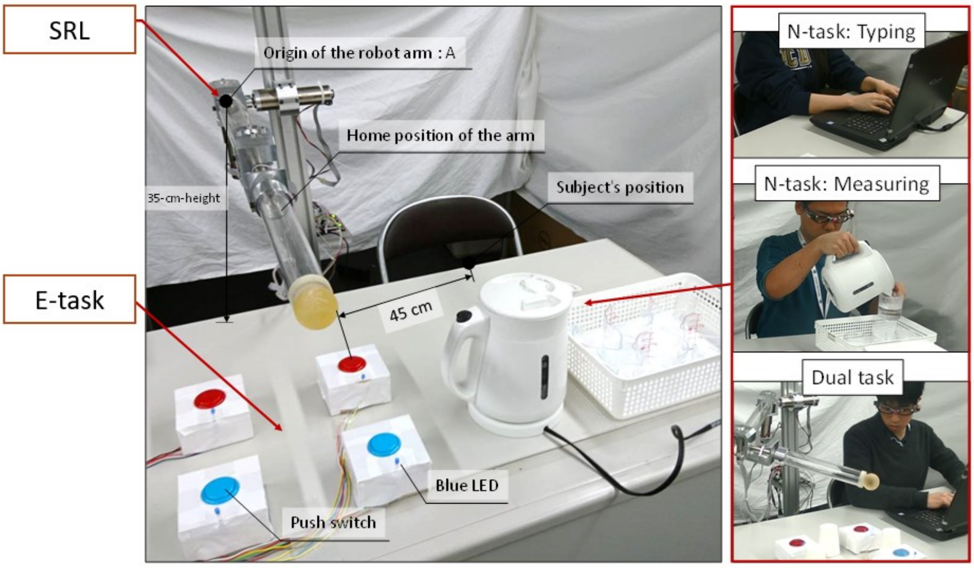


Fig. 17 Path instruction method using the head tilt

experiment consists of a task performed by the SRL (E-Task) and a task performed using the natural limb (N-Task). The difficulty of performing dual tasks using each operation method is verified by the task execution time when the two tasks are performed sequentially versus when they are performed simultaneously and the task performance when the N-task performed alone versus when it is performed together with the E-task. As discussed in Section I, this study focuses on tasks that may defy expectations of the superiority of the point-instructed method; for the E-task, this is the number of times the instructions are repeated, and for the N-task, this is the level of attention required. In this experiment, the E-task involves the subject operating a SRL to press a desired button without hitting an obstacle, and the N-task involves the subject performing two tasks that seem to require different levels of attention. These tasks are described in more detail in subsection 2.3.2 and 2.3.3.

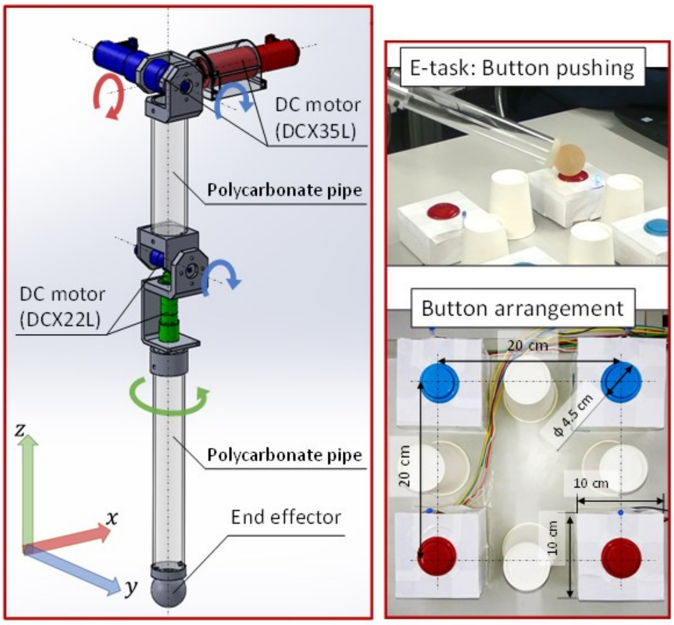
2.3.1 Overview

Fig. 18(c) provides an overview of the experimental environment. The subject sits on a chair in a defined position, with the N-task area just in front of them and the robot arm and E-Task area set up slightly to the side. SRL hardware is often wearable; however, in this experiment, the robotic arm is fixed to a pole at the height



(a) overview

(b) N-task



(c) SRL

(d) E-task

Fig. 18 Setting and overview of experiment

(a) Specific design of the robot arm. The two shoulder motors are Maxon DCX35L (gear: GPX42C, encoder: ENX16, controller: EPOS4 Compact 50/8 CAN). The movable range of the y-axis shoulder motor is 180°. The two elbow motors are Maxon DCX22L (gear: GPX26C, encoder: ENX16, controller: EPOS2 24/2). The movable range of the y-axis elbow motor is 180°. The end effector for pushing the button is a 3D printed 46-mm diameter ball. The arrival angle of each motor is calculated using simple 2D inverse kinematics. (b) Button and LED arrangement for the E-task. (c) Basic experimental environment. The arm position in the figure is the home position of direct reaching task. (d) N-tasks and dual-task setups.

of the subject's shoulder to reduce the effect of fatigue and misalignment. The robotic arm has a total of four degrees of freedom at the shoulder and elbow. The rotation speed of each motor at the shoulder and elbow is 4.5 rpm and 9 rpm, respectively, and the total length of the arm is 70 cm, which is approximately the same as the average arm length of a human adult [78]. The robot arm can reach all the buttons used in the E-task. More details on the actuators are provided in Fig. 18.

2.3.2 E-task setting

The E-task is a button-pressing task. As shown in Fig. 18(b), four push buttons and a pair of LEDs are placed on the horizontal surface of a desk. At the beginning of the experiment, a randomly selected LED lights up to indicate the button to be pressed, and the subject attempts to press the button by operating the robot arm using the operation interface. The next LED lights up 5 seconds after the button is pressed. This is one set of the trial and it repeated 6 times to finish the E-task. The time taken from the signal indicating the start of the experiment to the completion all trials is recorded as the E-task time. As mentioned in the previous section, the E-task is performed under the following two conditions to perform different number of repetitions of the point-instructed method:

i) Direct reaching task: There is no obstacle between the current position of the SRL and the target point (Fig. 18(c)); thus, the subject does not need to consider the arrival path. The SRL always returns to its default position before the start of each trial. Therefore, when using the point-instructed method, the subject can basically complete each trial by only pointing once.

ii) Indirect reaching task: There is an obstacle between the current position of the SRL and the target point; thus, the subject needs to consider the path to be reached (Fig. 18(b)). Therefore, when using the point-instructed method, the subject needs to add some pointer along the way and move it to avoid the obstacle as shown in Fig. 19. In our interface, pointing at points in the air is not possible, but by pointing at the floor or walls beyond its range of reach, the robot arm can be moved in that direction.

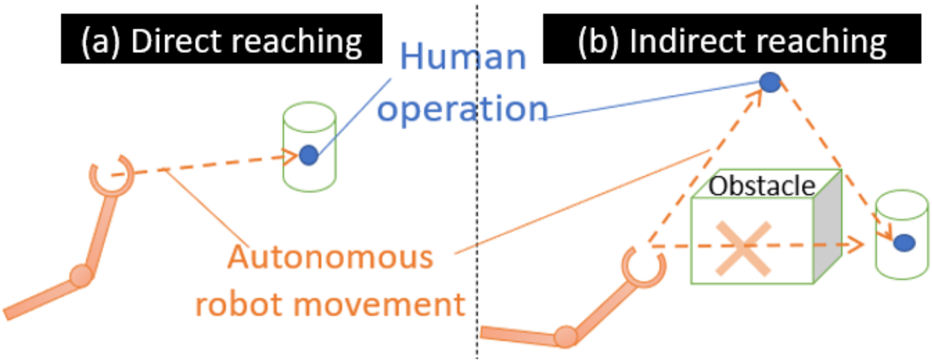


Fig. 19 Direct reaching task and indirect reaching task

2.3.3 N-task setting

The N-task comprises two tasks with different levels of attention. From the perspective of cognitive science, cognitive stimuli that involve language comprehension are considered to be among the factors that interfere with other tasks the most [79]. Therefore, in this study, we set up two types of tasks: one that requires language comprehension and another that mainly involves physical work.

i) Language task (typing): In this task, subjects type sentences displayed on a computer screen using a keyboard. Each subject types the same number of characters under the same conditions. Task performance is determined by the number of keys typed per second and the number of errors.

ii) ii) Physical task (measuring water): In this task, subjects pour a specified amount of water from a pot into a measuring cup (Fig. 18(d)). After completing the task, the amount of water poured is measured, and the deviation from the specified amount is recorded to quantify the N-task performance.

2.3.4 Procedure

Before starting the experiment, sufficient practice time was provided to use the interface for both the point and path instructed methods. Next, the subjects first performed the N-tasks (typing and measuring water) in a single-task condition and obtained standard values of performance and required time. Similarly, the E-task was performed in both the point and path instructed methods, and the standard values of the required time were determined. The order of these conditions was randomized for each subject. Next, when performing the typing task as the N-task, the E-task was simultaneously performed in the point or path instructed methods. Then, the same was repeated when the N-task was a water measuring task. In the case of the dual task, the time from the experiment beginning being signaled to the subject declaring all tasks completed was recorded as the required time. Six healthy adults in their twenties (5 males, mean age: 23.8 SD±1.6), who gave informed consent, participated in the experiment.

2.3.5 Result and discussion

Fig. 20 shows the performance of the N-task (typing, measuring water), and Fig. 21 shows the average time spent by the subjects in each E-task condition (direct or indirect) and each N-task condition (language task or physical task). For four graphs in Fig. 21, the left- and right-hand sides present results of the point- and path-instructed methods, respectively. Because there are two variables, irrespective of whether the N-task and E-task are performed sequentially or simultaneously and whether the method is point- or path-instructed, a 2-way ANOVA was conducted for each using the Bonfferoni method. This result is expected to be strengthened by increasing the number of subjects in the future.

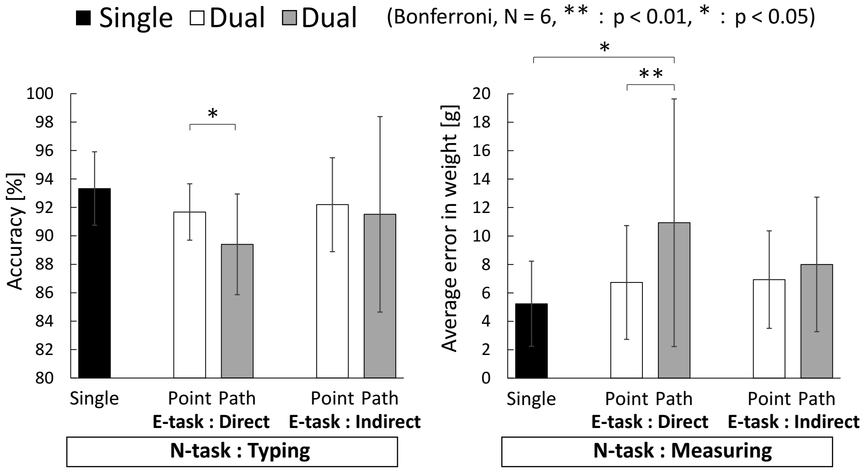


Fig. 20 Performance results for each N-task

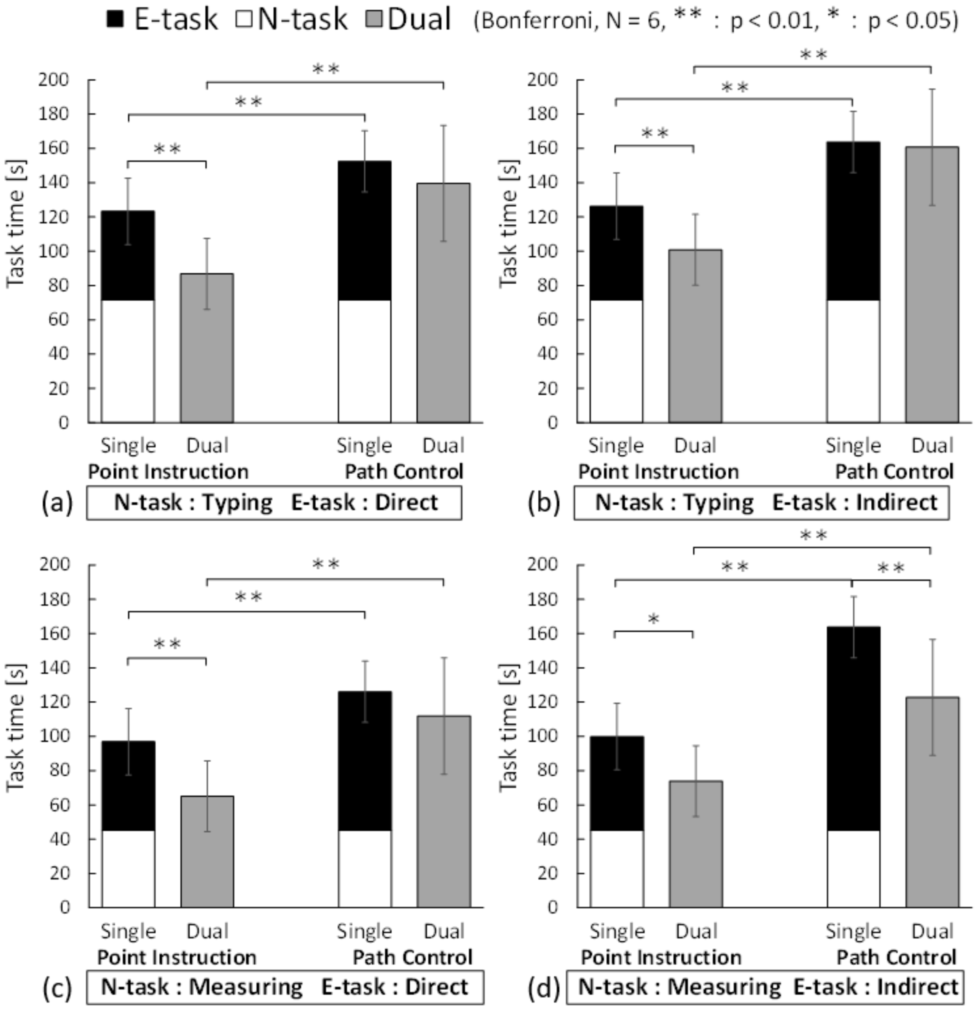


Fig. 21 Time results for each task

The figure shows the completion time in each task condition. Single completion time means the total completion time of N-task and E-task under a single-task situation.

2.3.5.1. Result of E-task and point instruction

From Fig. 21, the effectiveness of the point-instructed method with the E-task condition can be inferred by comparing (a)(c) and (b)(d). In all the four conditions, regardless of whether the E-task is direct or indirect, the point-instructed method significantly reduces the work time in dual-tasking from that in single-tasking. This suggests that the effect of switching cost owing to the increased number of concerned switches did not affect the work even if it existed at a cognitive level. In fact, in the N-task results presented in Fig. 20, the point-instructed method did not reduce the N-task performance in either the direct or indirect conditions. However, the average number of instructions added by the subject in the point instruction was 1.5 because the route for this detour instruction was relatively simple. In the future, we need to conduct a further investigation, with the number of instructions as a variable, and clarify the switching frequency that leads to the effect of switching cost appearing at the task level.

2.3.5.2. Result of N-task and path instruction

From Fig. 21, the effectiveness of the path-instructed method according to the required attention level of the N-task can be inferred by comparing (a)(b) with (c)(d). The results indicate that the dual-task work time is shorter than the sequential-task work time only when the physical task is performed and when the path method is implemented under the indirect condition because of two factors. First, when the N-task is a physical task that does not use language, the required attention level for the task is low, and the operations can be performed simultaneously in the path-instructed method. Second, the indirect condition requires a lower level of attention than the direct condition requires when performing operations in the path-instructed method. We expected the E-task condition to only affect the point-instructed method, but it may also affect the path-instructed method, which will be discussed in detail next. Because the attention levels of both the N-task and E-task were sufficiently low, dual-tasking was possible in the path-instructed method only under this condition. In other words, dual-tasking can be possible even in the path method when the required attention level of the N-task is low, but this may also collapse depending on the attention level of the path-instructed operation itself (e.g., whether one wants to operate carefully or roughly).

2.3.5.3. Discussion

Two hypotheses were assumed in this experiment: when the E-task is an indirect task, dual-tasking is no longer possible even with the point-instructed method, and when the N-task is a water-measuring task, dual-tasking is possible even with the path-instructed method. The results reject the former and partially prove the latter when the E-task is an indirect task. In addition, the subjects tend to think that the indirect task is easier than the direct task when the path-instructed method is used. This is supported by the fact that the performance in the N-task was significantly inferior when the direct task was performed with the path-instructed method than when it was performed with the point-instructed method. A hint for this can be found in the interview conducted with the participants after the experiment, in which they said, “In the Direct task, I tried to reach the target directly, so I tried to go the shortest distance as much as possible. In the case of the Indirect task, first I bypassed roughly the obstacle, and then, after getting close to the target, I seriously operated the remaining distance.” In other words, it is considered that even in the path-instructed method, the indirect task required less time to pay substantial attention to the operation and thus had essentially become similar to the point-instructed method.

The results of this study make two important suggestions. First, for the operating interface of the SRL, the point-instructed method is still recommended as it requires less attention time per input. In this study, the point-instructed method outperformed the path-instructed method in all E-task and N-task conditions and enabled dual-tasking. The dual task was also enabled in the case of the indirect task with the path-instructed method. This is not a classification of point- and path-instructed methods, but it rather highlights the need for further verification of the input method using the time spent per operation and the required level of attention as variables. The second suggestion is for the next approach, to evaluate the feasibility of dual-tasking for the same N-task by varying the input method along several axes: duration, frequency, and magnitude of attention directed at it. For example, if a task that requires attention for a certain period of time, such as 0.5 s, 1 s, 3 s, etc., is given as the E-task, with typing as the N-task, we can find the characteristics of the “duration” of the input method by examining how much the performance of the N-task is disturbed. If, for example, the results indicate that attention for 1 s does not affect the N-task performance, we can design the SRL operation input to be less than 1 s at a time, which can be easily used in a dual task.

This experiment also includes some limitations. For example, we adopted head movement as the common input modality for point and path instruction. If other modalities are adopted, the base attention level required for the operation will change. It required to be investigated whether other modalities can support the present results. In addition, mechanical errors in the SRL and eyeglass interfaces used in the experiments may have resulted in unexpected attention to the instructions in some trials. While these task settings in a real-world environment can yield practical results that are closer to the application, simulation task with tightly controlled conditions, for example in a VR environment, should be conducted in parallel.

2.4 Evaluation: effect of vBF

2.4.1 Overview

The purpose of the experiment is to clarify the basic characteristics of a face vector in aspects of the pointing accuracy and task execution time, and thus to evaluate voluntariness and intuitiveness as pointing modality of the SRL. In order to construct a dual-task environment, two independent tasks are set; a task performed by the SRL called E-task and a task performed by a natural body called N-task. Fig. 22 is the overview of task setting.

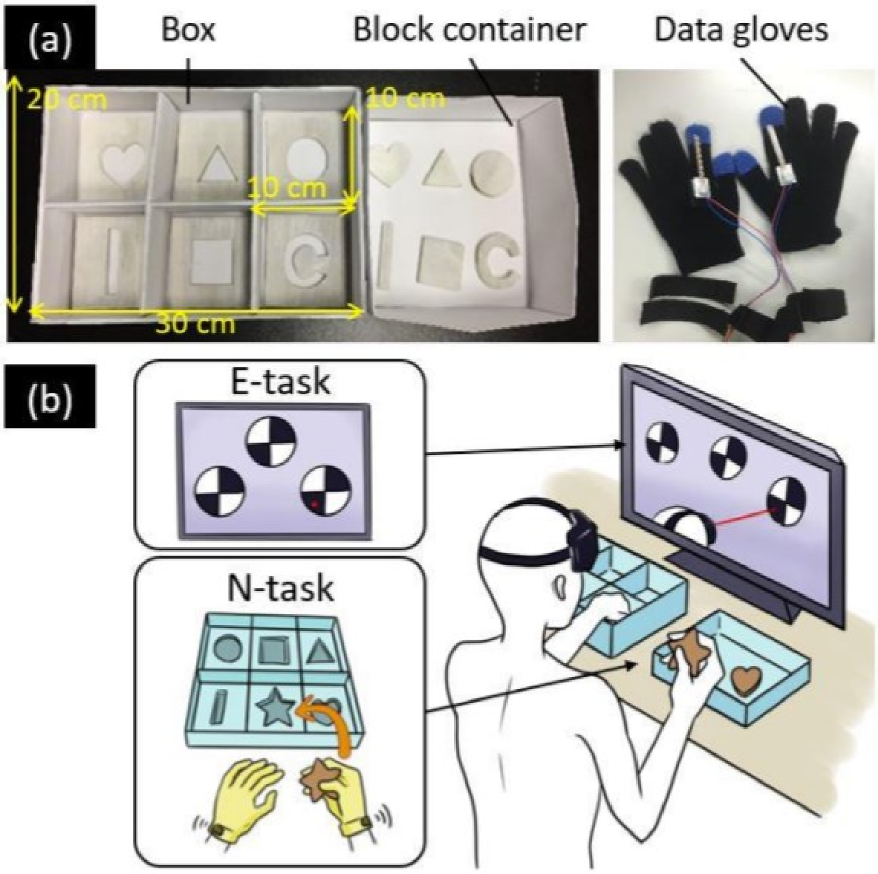


Fig. 22 Overview of dual task evaluation

2.4.2 E-task setting

The E-task is a target pointing task by a face vector. The requirement of the task is that the pointing error distance or direction can be measured without mechanical error of hardware. Therefore, the environment of the E-task was constructed in virtual reality (VR) using software Unity [80]. The experimental field is visually projected by immersive head mounted display, Oculus [81], accompanied by spatial scale equivalent to the real-world environment.

The experimental environment is set as shown in Fig. 23. 10 target markers are displayed on a vertical plane, which is about 70 cm forward from the subject, this distance refers to the maximum reaching range of the average adults assumed by their arm length [78]. A face vector is defined in the vertical forward direction from the center of the subject's face plane set by the Oculus, and its position and direction are constantly tracked in the Unity engine. Because the position of the subject's face

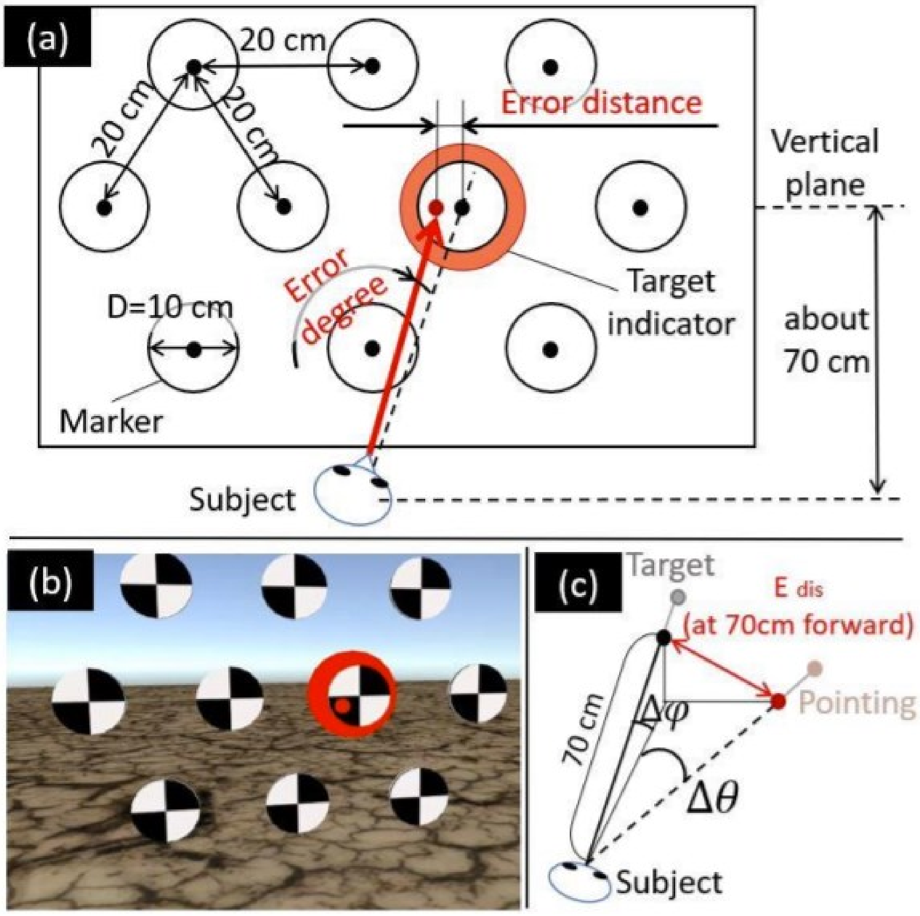


Fig. 23 E-task setting

is not static, the error distance E_{dis} at 70 cm forward from subjects can be recalculated using error degree from target direction θ and φ (Fig. 23(c)):

$$E_{dis} = 70\sqrt{\tan^2 \Delta\theta + \tan^2 \Delta\varphi} \quad (2)$$

After the start signal, subjects point at the center of the marker with the target indicator behind it using their face vector. The target indicator moves to change the target marker every 5 s at random, so subjects should continue to point at the center of the target marker indicated during that time period. In each time period, the error degree at 0.1 s before the indicator is switched is recorded. 6 time of target pointing as one set of trial, and two trials are prepared for each experimental condition.

2.4.3 N-task setting

The N-task is a shape discrimination task of blocks performed by natural human arms. One requirement of the task is that it can be performed with no visual information in order to separate required modalities and exclude the influence of alternately observing of tasks for condition simplicity. Another requirement is that the pause of human can be detected to confirm performing of the dual task at the moment of recording error degree in the E-task. Therefore, a task was set to touch the block and determine its shape as shown in Fig. 22 with a hand wearing a data glove which can record the acceleration of hand movement and bending of fingers.

As shown in Fig. 22(a), a box that is partitioned into six areas is provided and six wooden blocks with various shapes are given in a block container. At the bottom of each area, there are bottom panels with holes in six shapes that correspond to each of the block shapes. In the initial state, the subjects are blindfolded with Oculus and all six blocks are placed in the block container. After the start signal, the subjects pick blocks up at random, touch the holes in the bottom panel, and locate the area with a hole that has the same shape in its bottom panel as that of the block that the subject is currently holding. The subjects do not need to embed the blocks in the appropriate holes in bottom panel, and are only required to place the block in the correct area. The time from when experiment start cue was given to the point at which the subject declared that they had finished the task was recorded.

2.4.4 Procedure

Sufficient practice time was allowed for both the E-task and the N-task before the experiment was started. First, subjects performed each E-task and N-task in a single-task situation to determine the standard value of their scores. Next, they performed both E-task and N-task similarly for every E-task's condition as shown in Fig. 22(b). For both single-task and dual-task conditions, the order of trial in the E-task using simple face vector or with its vBF was random. The number of subjects was eight, and all of them were healthy adults in their twenties.

2.4.5 Result and discussion

2.4.5.1. Result and discussion of Pointing Accuracy

Fig. 25 and Table I show the average results for the error distance for each experimental condition denoted by (A)-(D) in section 2. Fig. 25 also shows the results of the analysis using two-way analysis of variance (ANOVA). We used this method because there are two conditions for each experiment, i.e., simple face vector or with vBF, and single or dual tasks, and all subjects were tested under all experimental conditions.

The condition (A) of simple face vector in a dual-task situation is closest to the actual use environment of the SRL in 4 conditions. The influence of vBF and of natural body movement for accuracy can be discussed by comparing this condition (A) as a basic condition to others. First, regards of vBF influence, the condition (A) is compared to the condition (C) that is in a dual-task situation and with vBF. There was a significant difference between the pointing accuracy of the condition (A) and (C), and thus the vBF is considered to be effective in improving the accuracy of instruction when using a face vector. Next, as for influence of body movement, condition (A) is compared to the condition (B) that is the case using simple face vector in a single-task situation. There was no significant difference between the condition

Table I Average error distance

Face vector condition	Task condition	
	Single task	Dual task
no vBF	5.52 cm	6.68 cm
with vBF	0.42 cm	2.00 cm

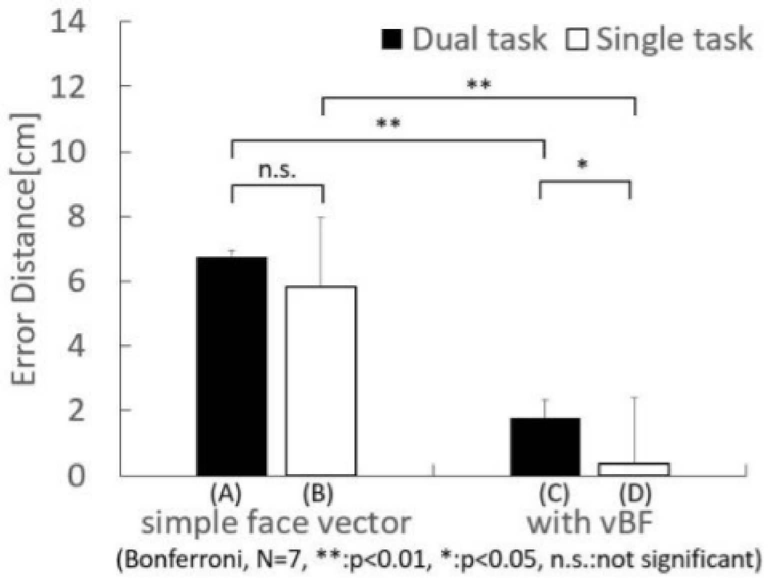


Fig. 25 Average error distance of pointing in each condition

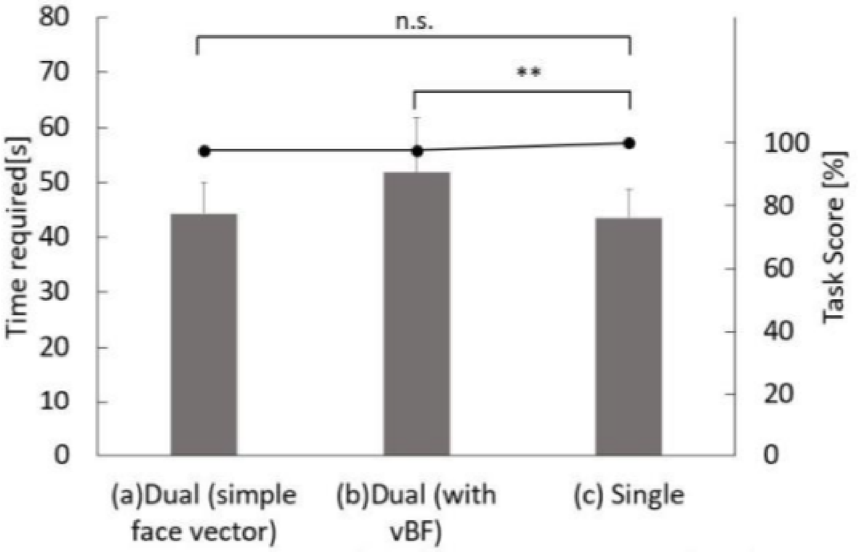


Fig. 24 Average time required to N-task and task score in each condition

(A) and (B). On the other hand, there was a significant difference between with vBF the condition (C) and (D), a single and dual-task conditions. These results indicate pointing accuracy is decreased by body movement due to body movement in dual-task situations, and additionally, instructed point can easily to be blurred if there was no vBF. Therefore, in aspect of accuracy, showing vBF of face vector is recommended because it can stabilize the instruction point and improve pointing accuracy when using proposed modality.

Validity of numerical value in Table I is difficult to discuss. Because the scale of objects assumed to be pointed in daily life is various from 1 cm width of a pen to 1 m height of a chair, and required accuracy cannot be determined in non-task-oriented assistant devices. However, these data become important values in order to design the hardware of a robot arm and an end effector.

2.4.5.2. Result and discussion of Pointing intuitiveness

Fig. 24 shows the average time required to perform the N-task and average task score. As previous part A, the intuitiveness can be discussed from N-task score and efficiency by comparing the condition (A) as a basic condition to others.

First, regards of the N-task score, there was no significant difference between each dual-task condition (A) (B), and the single-task condition (C). The result indicates that the cognitive load required for using face vector did not prevent the correct the N-task performance at least this difficulty level of the task. In order to discuss the limitation of cognitive load can be given to the N-task, more detailed verification is needed that the difficulty level is changed, for example, discrimination of heptagon and octagon for future work.

Next, regards of work efficiency, the condition (A) is compared to the condition (C) that is single-task situation of the N-task. There was no significant difference between the required time of the condition (A) and (C). On the other hand, the required time of the condition (B) which of face vector with vBF in the E-task, significantly increased compared to the condition (C). The reason for this result is believed to be that the subject pays too much attention to the vBF when it is available. If there is no vBF for a face vector, the subjects may want to point at the object less strictly because there is no way to know whether or not the point for which they are providing instructions is correct. The subjects were satisfied to point only intuitively at what they think to be the target point, and then pay more attention to the N-task soon after that. In contrast, if there is vBF for a face vector, the subjects may want to point more strictly at the object because they could determine the extent to which they had pointed beyond the correct target point. Therefore, it is assumed that the subjects pay more attention to object instruction in the sub task, and as a result, they tend to be negligent in performing the N-task.

Based on these discussions, it is suggested that cognitive load of the simple face vector is low enough to perform dual-task correctly and efficiently. On the other hand, there is a trade-off relationship in vBF, which increases pointing accuracy but increases cognitive load and decreases work efficiency. For this problem, the influence of proficiency to the pointing by face vector modality should be considered. If the error distance become decrease due to continuous using, one solution to this trade-off is remove the vBF when users accustomed to face vector operation. Other experiments are also necessary to discuss the influence of the N-task difficulty level and characteristics to modality intuitiveness. For example, the N-task of cutting vegetables with knife requires a large cognitive load and using vision information continuously. Such experiments will be set to perform in a real environment where mechanical errors and measurement errors should be considered. The basic characteristics of a face vector revealed in the VR environment with this paper play an important role to design hardware for these experiments or analyze results.

2.5 Chapter discussion

In this chapter, we proposed intermittent control as a method of operating the SRL that does not occupy attentional resources for a long time in a dual task, and developed an eyeglass-type device capable of pointing using a face vector. One of the problems that may be a negative factor for consuming attentional resources is that the instruction points by face vectors are not visible. In order to improve pointing accuracy and dual-tasking performance, we implement the visual biofeedback (vBF) of pointing location and conducted an experiment to evaluate the effect of vBF. The results suggest that although vBF improves the pointing accuracy, the user would rather allocate more attentional resources to pointing by making it visible.

Now we discuss issue (1) "In a fully manual operation that emphasizes voluntariness, a large amount of attention is taken to the SRL, making it difficult to efficient dual-presence task" from the development and verification of the operation system using a face vector. There was a trade-off between improving the pointing accuracy by presenting vBF and reducing the attention required for operation. This trade-off occurred even when we adopted intermittent operation instead of conventional fully manual operation. This is due to the assumption that the high voluntariness in intermittent instructions is meant to be the high accuracy of the instructions. One approach to resolving this trade-off is to allow the inaccurate or roughly instructions by other design elements in the system. It may be possible to reduce the attention required for it, while preserving the voluntariness of the operation. For example, the instruction error for pointing in the present study was about 6 cm without vBF. Conversely, we can address this problem by developing a robot hand that can absorb the error and robustly grasp the object even if the user instructs a point 6 cm away from the object to be grasped. For this purpose, we have developed a new robot hand that can absorb the instruction error as shown in Fig. 26. The fingers of this robotic hand are made of silicon material in the shape of a small bag, and the coffee powder is sealed inside. After contacting the object to be grasped, the air inside the fingers is sucked out, and the shape of the fingers is fixed according to the shape of the object. This kind of mechanism is called a jamming mechanism [82] [83], and this robot hand is equipped with three of these in a radial pattern. Even if the indicated point is slightly off from the object to be grasped, it draws the object to the center of the hand and deforms the shape of the fingers to enable robust grasping. We have performed object grasping of various shapes and scales with this hand, and confirmed that it can absorb errors of about 6 cm [84].

In this way, the pointing interface using a face vector can function according to the user's intentions even when the user gives "rough" instructions, by using it together with hardware that can absorb pointing errors. From the above, as the design theory of a SRL for dual task, it suggested that focus on reducing the attentional resources consumed rather than the accuracy of the instructions, and absorb the errors by other design elements such as hardware mechanism.

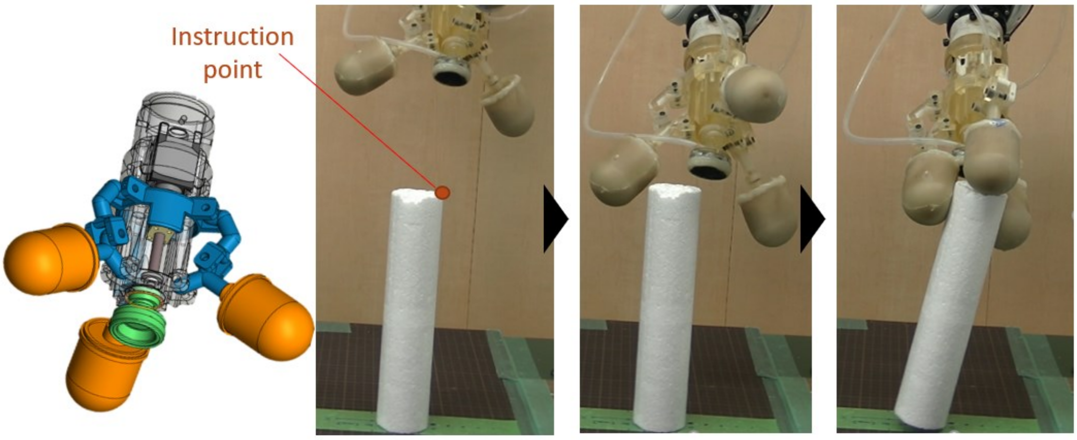


Fig. 26 3-finger jamming gripper for absorbing instruction error

Chapter 3: Feedback System

In this chapter, we will address issue (2), “the feeling of anxiety about the state of the SRL, such as in automated parts, causes user to pay attention to it repeatedly, making it difficult to perform efficient dual-presence task”. The problem of attention in this chapter is one that arises when understanding the state of the SRL. This chapter discusses the design elements of the SRL system to achieve efficient concurrent task by designing the FB system of SRL state and evaluating its usability in a dual-task experiment.

3.1 Issue and approach

When using a wearable robot, such as in the research of human augmentation, user can basically check the robot's operating status by looking at it directly, feeling the moments returned to the user as the robot moves, and listening to the motor sounds transmitted by the hardware. However, these are often considered to be a burden on human attention in dual-tasking. Consider a dual task in which the natural body cuts vegetables with a knife while the SRL puts used utensils and plates into the sink one by one for washing. If we use the face vector interface proposed in the previous chapter to give instructions, the robot will be instructed by pointing at the dishes to be grabbed and the point at which they are to be carried, but the robot will move autonomously between these points. During this time, the user may gaze at the work of the SRL several times to check whether the grasped plate is about to fall during transportation, whether the glass utensil is about to hit the surrounding area. Such unnecessary visual confirmation may cause frequent interruptions of the task on the natural body side, incurring switching costs and degrading the performance of the dual task. In order to reduce the number of these unnecessary visual confirmations, it is possible to take automatic functions such as adding an algorithm that detects obstacles and automatically avoids them [85], or increasing the number of functions that stop the operation when an abnormality is detected, such as falling a plate. There is also a system that sounds an alarm when an obstacle is approaching in the vehicle design [86]. However, it is not realistic to anticipate and consider all errors in advance, and it also causes automation problems such as strong task orientation and adaptability only to specific environments and

Fig. 27 Haptic feedback device for virtual reality environment [89]

tasks. Therefore, it is necessary to have a system that feedback the state of SRL information independent from the environment without using visual information, such as the proprioception of the additional body or the sense of touch, same as the natural body.

Previous research on sensory FB of the SRL often focused on the questions of how to faithfully reproduce the realistic and raw sensation transmitted to the robot arm or human arm [87] [88], and how to create it in the case of the SRL where the original part of such sensation cannot be defined. This is an extension of sensory FB research in conventional telepresence and VR technologies. Fig. 27 shows an example of an application for transmitting such raw sensations to the arms of a natural body when touching an object in VR [89]. However, if we consider the SRL with these features in terms of dual-task feasibility, there arises the problem of the upper limit of attentional resources. As suggested by the experiments in the previous chapter, the more information (visually explicit pointing positions) that humans need to process on the SRL side in a dual task, the lower the task efficiency of the natural body side tends to be. In the case of FB, the higher and more complex the dimensionality of the information, the more attentional resources are consumed by the processing, and the lower the efficiency of the dual task.

In this thesis, we aim to reduce the number of unnecessary task switching while always recognizing the state of the SRL by limiting and simplifying the FB information from the SRL side. There are various types of information from the SRL side, such as proprioception that conveys position and posture, force sensation that conveys where an object is touched, and tactile sensation that conveys the softness and temperature of the touched object. In these information, we selected the three-dimensional coordinates of the hand position as the most representative and important one in the operation. The requirements for the modality to transmit this information are that it must be something other than vision, and that it must be able to intuitively transmit the sense of three-dimensional position. In general, vibration, sound, and force are commonly used as FB modality for systems [90]. For example, Hashimoto et al. presented the posture of a two-joint robot arm by a vibration frequency of the two vibrators which are placed on the back of user [91]. In addition, phenomenon called phantom sensation has been used to represent the position of a robot using vibration [92]. By vibrating the right side of two vibrators at 100 Hz and the left side at 50 Hz, a vibration of 75 Hz is created in the middle of the two vibrators. In this thesis, we attempt to represent the position of the hand of SRL using vibrators, because vibration is a good method for position presentation due to its intuitiveness and freedom of resolution.

3.2 Prototype development

In order to reduce the number of unnecessary visual checks on the SRL side and to improve the efficiency of dual tasks, we take an approach of recognizing the state of the SRL without using vision by using an array of vibrators, to represent simple information such as the three-dimensional coordinates of the hand position. In this section, we describe the development of a FB system that satisfies the above functions.

There are several ways to represent a three-dimensional position in space, such as presenting x, y, z in a Cartesian coordinate system or r, Θ, φ in a polar coordinate system. When placing the vibrator on the surface of the body, user's back and abdomen can be candidate as the placement position, where the vibrating display can be arranged over a wide area and where it does not overlap with the two arms used for natural body-side work. In this study, we selected the abdomen for the placement of the vibrators, and used a belt-like hardware base wrapped around the abdomen. This is because the back is two-dimensional plane, while the abdominal circumference allows three-dimensional placement of the vibrator in a hollow cylinder. The three-dimensional position of the hand is represented using a polar coordinate system centered around the belly button, as shown in Fig. 28. Theta and phi are expressed by the position of the vibration, and r is expressed by the frequency of the vibration. The vibrators were placed every 15 deg in the horizontal direction, referring to the fact that the two-point discrimination threshold of the human abdominal region is about 3-4 cm [93] and the average waist circumference of an adult is 88 cm [78]. By connecting several of them vertically, it is possible to represent the position of the hand in three dimensions. Because the torso cross section is not a true circle but an oval, the vibrators can be easily attached and detached so that it is possible to finely adjust the position according to the individual's figure after wearing. With regard to the vibration frequency, the frequency difference that human can easily distinguish is known to be follow the exponential of 2 [94]. Thus, for example, when the frequency is 25 Hz at 60 cm of radius, it becomes 12.5 Hz and

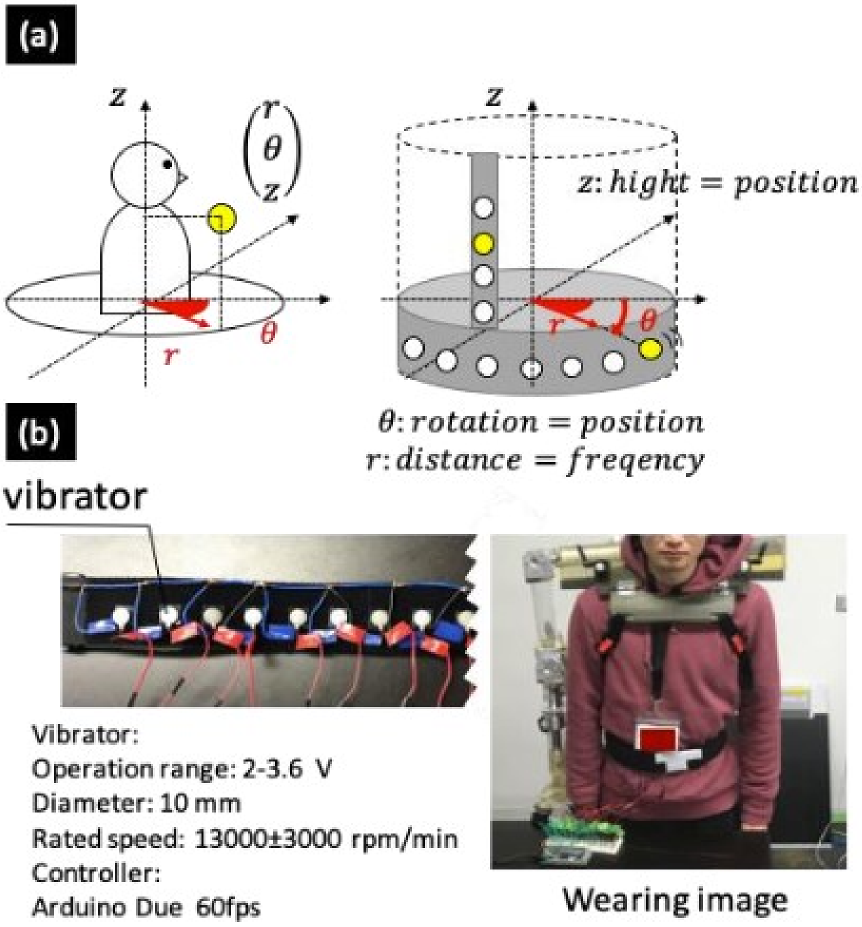


Fig. 28 Haptic belt for detecting the position of end effector

6.25 Hz as radius increases every 3 cm (away from the human). Detail information of the system is mentioned in Fig. 28(b).

The vibration FB belt developed in this way can transmit the motion status of the SRL through somatosensory perception even while the user is paying attention to the task at hand on the natural body side. On the other hand, it is unclear whether the attentional resources required for this FB information processing do not affect the task on the natural body side. This system pursues the simplicity by limiting FB information to only hand position, as opposed to the conventional FB systems that pursue realistic sensation. However, there is possibility that giving FB information is itself something that consumes a large amount of attentional resources. In that case, other modalities and methods should be considered. On the other hand, if the current amount of information does not affect the dual task, we can consider adding more information to FB (e.g., the feel of the touched object as well as the hand position).

On the contrary, it is also possible that the amount of attentional resources devoted to the task on the natural body side may affect the accuracy of the hand positions that the user identifies by FB. If the task is simple, such as the natural body side is mixing a pot, the user can use the information from the FB to sense exactly when the SRL's hand is at the target location and switch tasks appropriately. On the other hand, in the middle of a difficult task such as cutting vegetables with a knife, the user does not have time to even pay attention to the information processing of the FB, and it is possible that the robot arm has passed the destination where the it should be stopped when the user notices it, even though the information of the FB has been input. Thus, it is also important to clarify the positional accuracy of the user's hand that can be identified by the FB in both single-task and dual-task conditions. In the design, the transducers are placed at 15-degree intervals. Therefore, it is estimated that the FB can locate the hand with an accuracy of about 10 cm for a 70-cm-long arm under the condition that only a single vibrator vibrates at a time without using phantom sensation.

In the next section, we use the developed FB system to verify the accuracy of identifying these positions and the usability in dual-tasking in a two-step procedure. First, we clarify detecting accuracy of the SRL's hand by the FB belt under two conditions: one is when the FB belt only identifies the hand positions, and the other is when the FB belt identifies the hand positions while performing other tasks. Next, we investigate whether being able to identify the hand position with the FB belt improves dual-task performance by reducing the number of unnecessary SRL state checks for the user.

3.3 Evaluation: detecting accuracy

3.3.1 Overview

The purpose of this measurement is to determine the accuracy of detecting the position of the robot hand using the proposed system in single-task and multi-task situations. We also verify the effectiveness of the proposed system by comparing its detection accuracy with that of a robot arm only without the feedback system. The subject wears the robot arm and plots the hand position of the robot arm on a test paper (Fig. 29(c)) randomly set by the operator. The following four experimental conditions were set according to the feedback belt condition and the task situation.

A) No feedback / single task (drawing only task)
B) With feedback/single task (plotting task only)
C) No feedback/Multiple task (with calculation)
D) With feedback/multiple tasks (with computation)

The hardware of the robot arm is the one we developed in other study for multitasking [95] as shown in the Fig. 29(b). The total weight is about 7 kg and the arm length is about 70 cm, and the shoulder joint rotates in the pitch and yaw direction at an angular velocity of 5 rpm. The dynamic momentum and standing centroid vibration which occurs when the robot arm moves should be canceled to reduce user's fatigue, on the other hand it may be a clue information to know the hand position without a feedback system. Therefore, in this measurement, we conducted tasks with wearing the hardware which has no cancellation of the dynamic momentum, and clarify the effect of the development system by comparing to the just wearing robot arm condition.

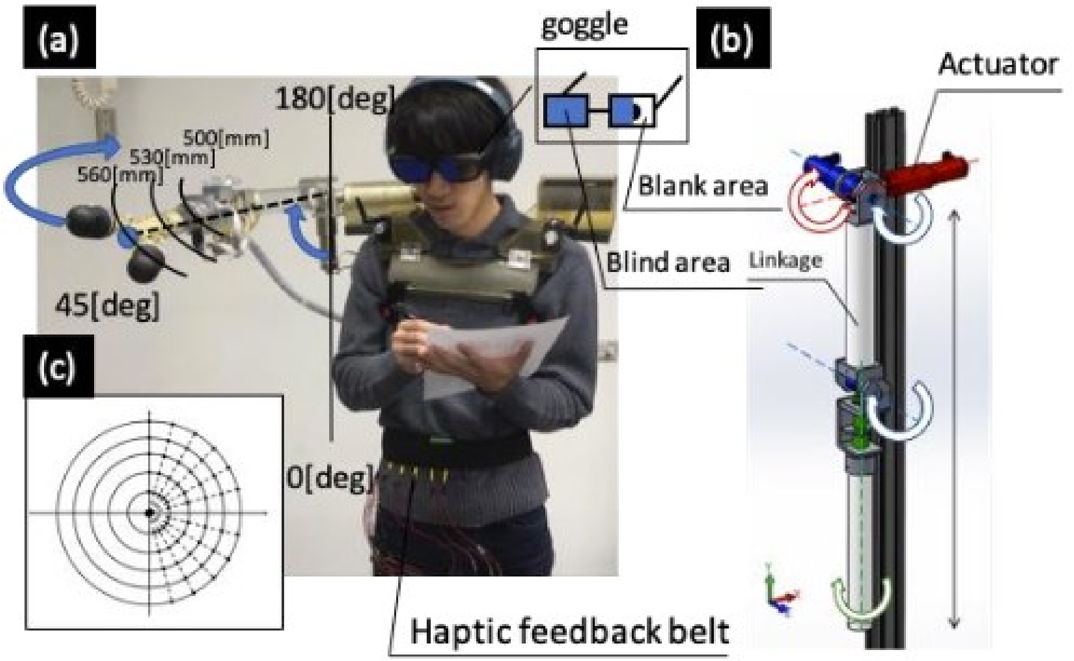


Fig. 29 Settings for measurement of detecting accuracy

3.3.2 Settings

As for the plotting task, Fig. 29 shows an overview of the measurement environment. The subject wears the robot arm and stands in a designated position. The initial posture of the robot arm is stretched to forward from the subject and parallel to the floor, and it can move in a horizontal plane within a range of 0 deg to 180 deg (Fig. 29(a)). Subjects wear a goggle that arm existed area is filled with black masking so that they can not obtain the robot hand position information by seeing. Subjects also wear the earphone so that they can not estimate the robot hand position from sound of vibrators and motors. A pen and recording paper as shown in Fig. 29(c) were given to the subjects, and all these materials can be seen through the blank area on the mask goggle.

As for the calculating task, subjects try to subtract a certain number from other number repeatedly, for example subtracting 7 from 1000. This method is often used as a parallel task of multitasking [96]. Subjects continue calculating task while plotting task has been performed.

3.3.3 Procedure

Before the measurement, a training period is given to subjects to use the feedback belt. In a 10 minutes training period, the robot arm keeps moving randomly, and Subjects look the robot hand position and associate it with the feeling of feedback vibration. After the start cue of the plotting task by the operator raising the hand in the blank area of the masking goggle, the operator moves the robot arm to a random position, and he raise the hand again when the movement is complete. Subjects plot a point on the recording paper where they think a robot hand is, and this is the cycle of one trial.

After the plotting, the operator moves the robot arm to the next random position within 5 s, and subjects plots the hand position again. Trials are repeated 10 times for each of the four conditions A) to D). In condition C) and D), the calculating task is performed simultaneously, and subjects say the result every subtraction. The order of the conditions is random for each subject.

Recorded data in plotting task is the actual coordinates of the hand in each trial, and the coordinates plotted by the subject, and error distance between them. In addition, the reaction time from when the operator completes the movement of the robot arm until the subject performs plotting, and the overall task time for one condition are also recorded. In the calculating task of the condition C) and D), the number of subtraction times and correct answer rate are recorded. The number of subjects was 6 and all of them were healthy adult in twenties, no one has experience with this device and habit of using wearable arm in a daily life.

3.3.4 Result and discussion

Fig. 30 shows the detecting error distance in each condition. This figure also shows the results of two-way analysis of variance (ANOVA), because we set two factors in the measurement for all subjects, i.e., without or with feedback belt and single or multiple task situation. In both single and multiple task conditions, the error distance was significantly reduced when using the position haptic belt, and the detecting accuracy was improved by about 7 cm on average. The result suggested that the position haptic belt can improve the detecting accuracy even in the condition that dynamic momentum was given to users. Validity of numerical value of detecting accuracy is difficult to discuss because required accuracy is depending on task especially in daily life environment. However, this value is a new knowledge as real-time detecting accuracy of position using vibration feedback and would be important reference when comparing to detecting accuracy using other modalities.

Fig. 30 also shows that there is no significant difference of detecting accuracy between the single task situation and the multiple task situation under the same feedback condition. The reason is considered not only because the feedback information was simple enough and not to interfere the parallel task, but also because the required attention level for the parallel task was very low. This is also indicated by the result that there was no difference in the correct answer rate of calculating task between the condition of with and without feedback system. Fig. 31 shows the correct answer rate of the calculating task in the condition C) and D). Therefore, in the next chapter, we will verify how the feedback information of robot hand position affects task performance in the case where the parallel task requires a large amount of attention.

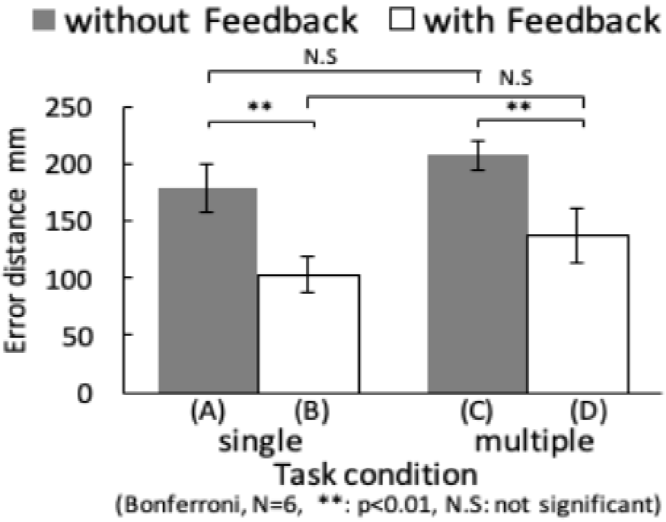


Fig. 30 Detecting error distance in each condition

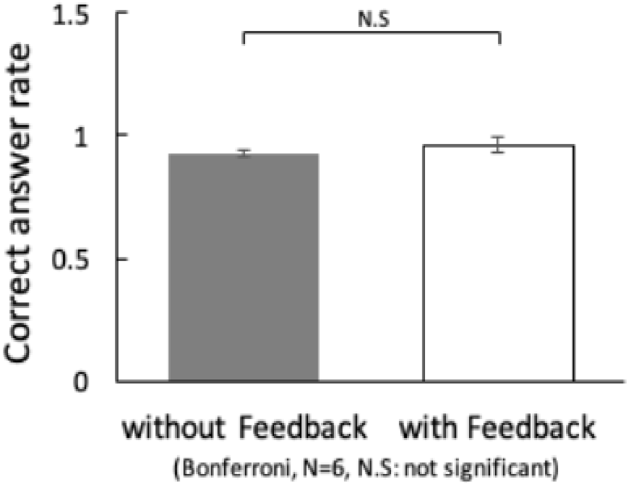


Fig. 31 Correct answer rate of calculation task

3.4 Evaluation: User study

The purpose of this case study is to discuss the influence of position feedback information of the robot hand to the multiple task situation. The effectiveness of the system is verified by comparing the task score and subjective evaluation to the case of only using the robot arm without the feedback system.

3.4.1 Overview

The subject performs a point stopping task by the robot arm and water pouring task by their natural arms as the multiple task situation. The point stopping task is to stop the robot arm at the target point, and the water pouring task is to pour the water to the target amount. Both of task should be performed as accurately and fast as possible and requires large amount of attention. Since the purpose is to know the influence of feedback information given by position haptic belt to the attention allocation, the robot arm was fixed to the pole at the height of the subject's shoulders in order to avoid that subjects are paying unnecessary attention to the physical burden with wearing. The structure of the robot arm and experimental conditions conform to C) and D) of the measurement chapter.

3.4.2 Settings

As for the point stopping task, Fig. 32 shows an overview of the experimental environment. Subjects sit in a designated chair in front of a desk, and a grid of 10 cm square is displayed on the desk which covers the range of the robot arm can move. The scale of this grid is referred to the result of the detecting accuracy in the measurement chapter. The robot hand can move at an angular velocity of 5 rpm in the range of 0 to 180 deg on a circumference of a radius of 65 cm centered on a pole. This area is set to be out of center vision field when subjects look at the parallel task

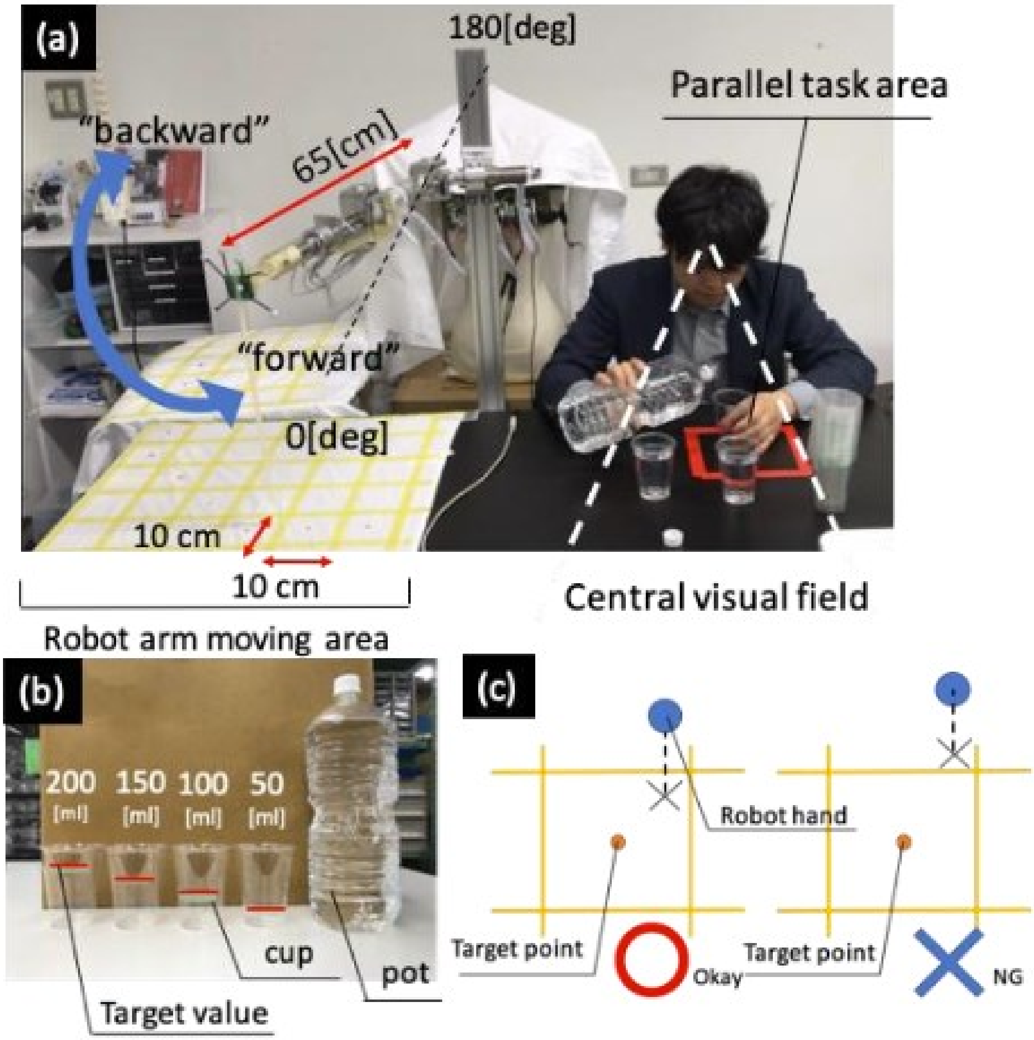


Fig. 32 Settings for user study of FB system

area. A thin stick is attached to the robot hand in the vertical direction so that the position of robot hand in the grid can be easily confirmed.

As for water pouring task is always performed in the parallel task area as shown in the Fig. 32. This area is within the central vision field when the subject is sitting at a designated position. A pot which filled with 2 L of water and several measuring cups are on the table (Fig. 32(b)). The measuring cup with a line on the target value, and there are six types of target value as 50, 100, 150, 200, 250 and 300 ml. The operator replenishes random types of cup when subjects complete one pouring. The subject can not return the water to the pot if it has filled more than the target.

3.4.3 Procedure

A 10 minutes training period is given before the experiment same as the measurement. Before the trial, the operator points at the center point of a grid cell with a laser pointer, and the subject see it and confirm the position. The subject then returns the face to the parallel task area, and the operator moves the robot arm to a random initial position. With a trial start cue by operator's voice, the robot arm starts to move in the direction of backward or forward as shown in the Fig. 32(a). When the subject thinks that the robot hand has come to the target position, they say "stop" to stop the robot arm movement. If this stopping position is within the area of the target grid cell, the trial is over. If not, the subject says "backward" or "forward" to move the robot arm and say "stop" again at a position they considers to be correct, and repeats this until the robot hand has come in the target grid cell. All trials are performed in multiple task condition with water pouring task and the subject can only pour water while the robot arm is moving. 10 trials are performed for each experimental condition C) and D) which defined in chapter 3.

Recorded data in point stopping task is the number of corrections until the robot hand to be in the target gird cell and the overall task time for each condition. In the water pouring task, the error volume by weight which is the difference between the

Table II Questionnaire of subjective evaluation

No.	Questionnaire
(1)	I can easily imagine the position and movement of robot hand.
(2)	I can concentrate the water pouring task.

actual poured amount and the target amount, and the number of used cups are recorded. After all the experiment is over, subject answered the questionnaire using a 7-step Likert scale as a subjective evaluation. The Table II shows the question items. There were two subjects (A and B) in this case study, both of them experienced previous measurement task.

3.4.4 Result and discussion

Fig. 33(a) shows the average number of corrections and the number of visual confirmations in the point stopping task for each of subjects A and B. The Fig. 33(b) also shows the average error volume and number of trials for the water pouring task. The figures regarding the number of visual confirmation and error volume also shows the result of a simple T-test because the number of trials depended on each task. As shown in the figure, when there is no feedback information, subject A tends to increase the number of corrections, while subject B tends to increase the number

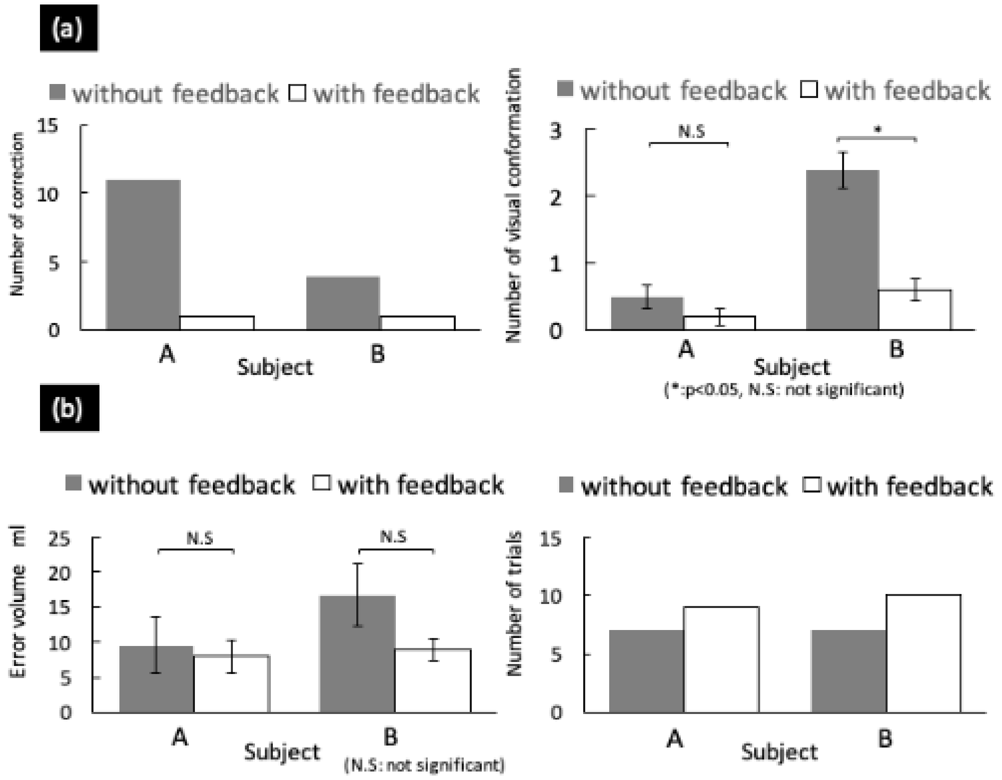


Fig. 33 Result of two subjects

(a)Number of correction and number of visual confirmations in the point stopping task. (b)Average error volume and number of trials in the water pouring task.

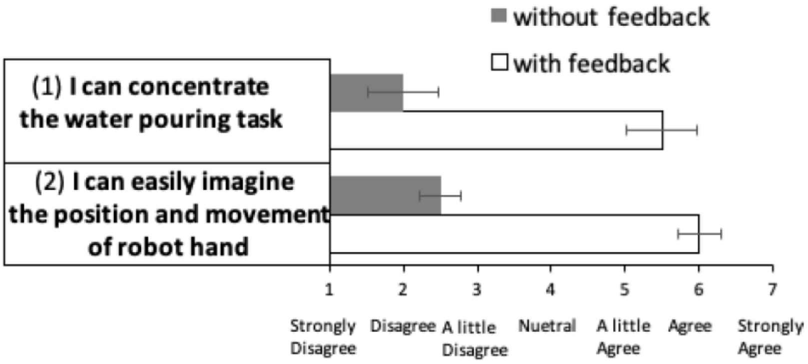


Fig. 34 Result of subjective evaluation

of visual checks. In any case, it is suggested that the feedback system is useful to perform parallel tasks efficiently, since both subjects were able to do more trials in the water pouring task compared to the conditions without feedback system.

Fig. 34 shows the questionnaire results of subjective evaluation. As a whole, both subjects had a positive impression for the feedback systems in this multitasking situations. Also in the interviews with subjects after the experiment, one subject said that "I could concentrate on the water pouring task at ease because I could feel the movement of the robot arm". This indicates that position feedback information may lead to a sense of security or control to the robot arm. The psychological analysis of the attention allocation in the multitasking is required because the result shows the possibility that the task efficiency or score is affected not only by the switch cost but also by subject's mental condition.

3.5 Chapter discussion

In this chapter, we discussed the effectiveness and limitations of the proposed FB system from two evaluations. The evaluation of detection accuracy suggested that the system can intuitively know the position of the robot hand on the horizontal plane without degrading the task performance even when the users not pay much attention to the FB. The evaluation of user study also suggested that the FB of the robot hand position improve the performance of the main task. These results indicate that the somatosensory feedback system of the hand position is effective in terms of efficient attention allocation in dual tasking. In addition, considering the setting position of the robot arm in the experiments, the FB is effective in the case of not only dual-presence task but also dual tasking in single-presence where it is easy to see and feel the movement of the robotic arm. Since this result was obtained using a system with two-dimensional information, it requires to be verified for a system with three-dimensional information. It is also necessary to verify the usability of the feedback system when it is combined with other feedback technologies such as phantom sensation, or when it represents more information such as the tilt of the robot's hand and the open/close state.

Now we discuss issue (2) "The feeling of anxiety about the state of the SRL, such as in automated parts, causes user to pay attention to it repeatedly, making it difficult to perform efficient dual-presence task" from the development and verification of the hand position FB system using vibration belt. In the evaluation of the usability, the number of times the subject checked the arm tended to increase in the case without the FB compared to the case with the FB. Therefore, as a design theory of the SRL for dual tasking, it suggested that to have a FB system which inform the posture or working state of the SRL is effective to reduce the attentional resources required to the SRL, especially when there is the part of automation in the operation method.

In addition, the development of a FB system that can inform the state of the SRL by somatosensory perception is not simply to save switching costs in dual-tasking, but also has another development. It is a possibility of contribution to induce embodiment to the SRL, that is, the users feel the SRL as their own body, not just as a tool or a robot arm. In the conventional study, three major conditions are known to be necessary to induce embodiment in an object [97]: the sense that the object can be moved independently and voluntarily by the user (agency) [98], the sense that the object belongs to the user (ownership) [99], and the sense that the object exists in the position of the body image that the user envisions (location) [100]. Research on the induction of embodiment has been conducted for a long time [101] [102]. For example, the rubber hand illusion is a famous experiment [103]. When a rubber hand is placed right next to the subject's hand, and the subject's natural hand is hidden, experimenter simultaneously making brush strokes on the same part of the rubber hand and the subject's hand, the subject begins to feel the rubber hand as their own hand. These experiments and conditions for embodiment have been discussed on the premise of inducing the embodiment of an existing body part (e.g., hand) into an object such as a rubber hand or a robotic arm. However, it is unclear that whether the same phenomena and conditions can be applied in the case of SRL's embodiment, which is a body part that did not originally exist in the body scheme. In addition, it is unclear that whether the embodiment of the SRL can be regarded as the same sensation as the embodiment of the natural body. However, the ability to obtain the posture of SRL through somatosensory perception may contribute to the enhancement of ownership or location, and to the induction of embodiment in the SRL. In such a case, how the induction of embodiment in the SRL affects the attention allotment during the dual task is also an issue to be discussed in the future.

Chapter 4: Dual-presence System

In this chapter, we will address issue (3), "dual-presence increases the amount of environmental information that needs to be processed, which takes up a large amount of attention and makes it difficult to perform efficient dual-presence task". The attention problem we are discussing in this chapter arises in the presentation of information in dual-presence, where we have to decide how to process the information from each of the two locations. In this chapter, we design a dual-presence system, evaluate its usability in a dual-task experiment, and discuss the design elements of a Detachable body system to perform efficient dual-presence task.

4.1 Issue and approach

In the dual presence task, a natural body and a Detachable body are placed at two different points and operated simultaneously. As shown in Fig. 35, the user requires to process information from two bodies (natural body and Detachable body) and two environments (environment A and environment B) at the same time. As for the information of the body, users can obtain the information of the natural body by their own somatosensation and vision, and the information of the Detachable body by using the FB system developed in the previous chapter [104]. On the other hand,

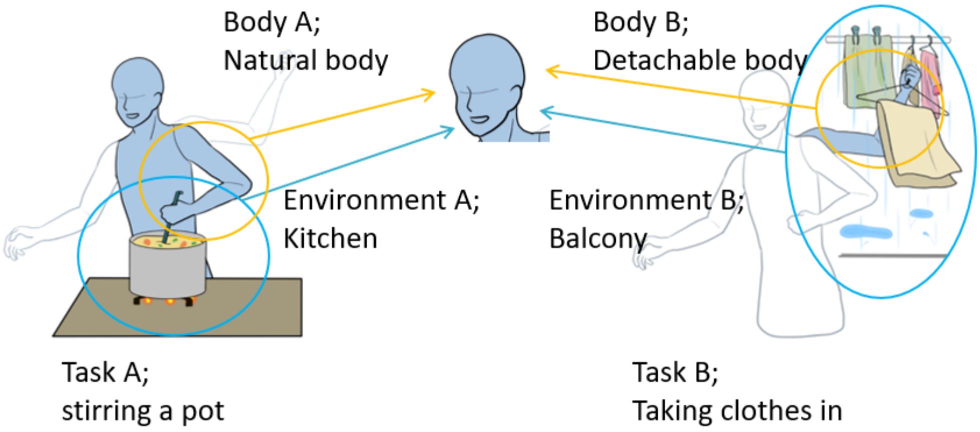
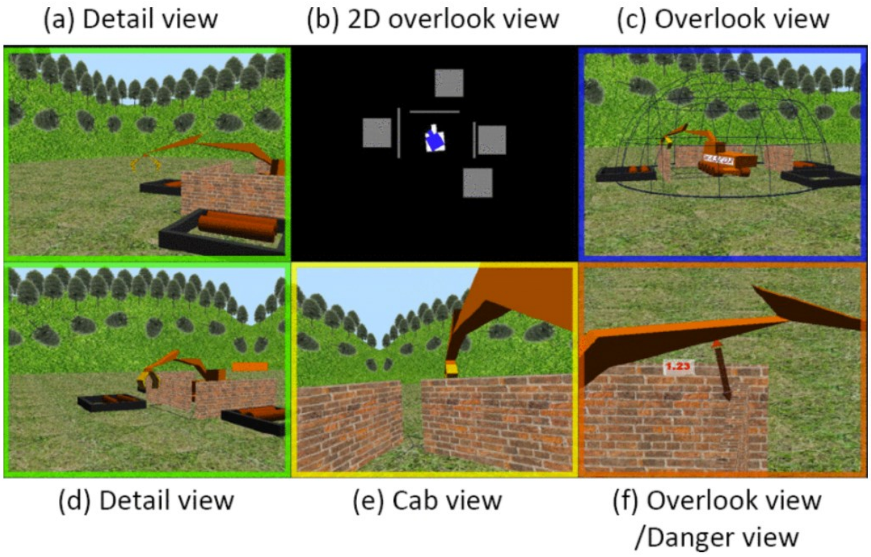


Fig. 35 Dual-presence task require to process two bodies and environments information



(a) Detail view (b) 2D overlook view (c) Overlook view

(d) Detail view (e) Cab view (f) Overlook view /Danger view

Fig. 36 Multiple display on the construction system

as for the information of the environment, if the environment on the side where the user's natural body is located is A, the user can obtain information on environment A by his or her own vision, but information on environment B is difficult to obtain. This difficulty increases as the distance between environment A and environment B increases. Therefore, for dual-presence tasks, it is necessary a dual-presence system that allows users to obtain information about environment B at the same time as information about environment A, while their natural body is in environment A.

Systems that can present multiple work environments at once have been used mainly in teleoperation of construction machinery or surveillance system [105]. For example, when remotely operating a construction equipment, a single screen can be divided to show some images, such as an aerial shot of the machine's position, an enlarged image of the grapple area, and images of the machine from the front and side (Fig. 36 [106]). In the control room of a nuclear power plant, images of various locations are displayed separately on each display so that monitors can view them all at once [107].

The two images that required to be presented this time are the environmental image of the natural body side and the environmental image of the Detachable body side. There are various methods of presenting the two images, such as dividing the screen and displaying them side by side on the right and left, or showing small thumbnail view on the bottom of main screen. Other systems have been proposed, such as superimposing a semi-transparent screen to make the user more aware of the sense of straddling two environments [59]. Since the purpose of our dual-presence system is to conduct physical task in two locations, manipulation is assumed to be performed in both environments. For manipulation, it is said that the most efficient way to work is to present the image from the first-person view [108], and the larger the screen, the more details can be observed. High immersion also improves the performance of remote work [109]. In order to satisfy these requirements, we can consider a method of superimposing two transparent images that can present both environmental images at the maximum size, or a method of presenting small sub image thumbnail on the bottom of the main image that can present the first-person view of main environment. However, in the method of presenting thumbnail image, user may have to pay large attention to the sub environment in order to recognize what is happening in detail simply because the image is small. Furthermore, switching between the main screen and the secondary screen may induce unnecessary switching, which was a problem in the design of the FB system. For this reason, we decided to use the method of superimposing two images. The application of this method to multiple screens instead of dual screens will be discussed in Chapter 6. On the other hand, we are concerned about the negative factor of consuming attentional resources when presenting screens in the superposing method. It is difficult to distinguish between images in this method. If attentional resources are consumed in identifying this information, the performance of dual-presence task may be decreased.

Therefore, we propose a disparity-based environment presentation system in which two images are projected on a screen with depth difference, and the images are distinguished by the binocular disparity of the user. This method of distinguishing images by disparity is one whose discriminability has been verified in some studies [110] [111]. By reducing the attention required for the user to discriminate between images, we aim to free up attentional resources and prevent performance degradation in the dual task.

Even in single-presence situation, it can be interpreted that the users process the image of two very near environments. In this respect, even in the single-presence state, the two tasks were visually separated entities, and the task switching between the two environments by moving the vision field between them occurred. However, there are several major differences between the single-presence and dual-presence cases. One is that in single-presence, the two tasks are performed adjacent to each other, so it is easy to recognize the positional relationship between the tasks. Moreover, this is consistent with the spatial location of the visual field being presented, which makes it possible to intuitively identify which visual information corresponds to which task. In the case of dual-presence, it is assumed that the user will be dealing with two tasks that are sometimes far away apart, for example, the US and Japan. In this case, it is difficult to identify which image information belongs to which task because the direction the user is facing and the positional relationship between the tasks are difficult to figure out. Another reason is that in single-presence, the subtask is performed very close to the main task, so the user can recognize the environmental information of the subtask using information other than visual image, such as the sound of a pot boiling. On the other hand, in dual-presence, the environmental information of the subtask is provided almost exclusively by vision.

4.2 Prototype development

In order to reduce the attention required to distinguish between the two environments while maintaining the ease of manipulation in the two environments, we took an approach of superimposing the transmitted images using a binocular disparity (hereinafter just "disparity"). In this section, we describe the development of an environment image presentation system that satisfies the above functions. In addition, we develop a prototype of an interface for dual-presence tasks by integrating it with the existing operation system and FB system.

The concurrent vision presentation system consists of two cameras and an immersive Head Mounted Display (HMD). One camera is placed at the front of the HMD on the natural body side, and the other camera is placed at the head position against the arm position on the detached body side. The camera angle is always synchronized with the angle of the HMD by a servo motor. In the HMD, transparent images from the two cameras are displayed and superimposed to enable disparity.

Here, we show the integration procedure with the operation system and FB system. As for the operation system, the distance sensor and IMU sensor used to acquire the face vector can be changed to a system based on a camera module that plays the role of a head on the remote side, by mounting it right next to the camera on the remote side used in the environment presentation system. A laser pointer can also be attached to the camera module in the same way when it is used as a function to indicate a point. As for the FB system, since the modalities and body parts (vibration array to the abdomen) used do not overlap with other system, it can be achieved by simply wrapping it around the waist. Fig. 37 shows the integrated system for dual-presence task contains concurrent vision presenting system and concurrent proprioception presenting system.

The interface for dual-presence tasks has been developed to: 1. allow manipulation with little attentional resources by intermittent control, 2. reduce switching costs by vibrating FB of the hand position, and 3. reduce the cost of discriminating between two environmental information even in dual-presence by disparity. At present, 3 has not yet been verified, and it is unclear whether the disparity will reduce the required attention for environment discrimination or improve the performance of the dual task. In addition, each of the manipulation and FB systems has been designed to consume as little attentional resources as possible, and it has been verified that the use of only each device contributes to the improvement of dual-task performance. On the other hand, when all of them are integrated, the problem of the total amount of attention resources arises again. For example, in the FB system alone, the processing of FB information did not degrade the performance of the main task and was contained in small attentional resources. However, when the system is used simultaneously with a concurrent vision presentation system, the attention resources required as a sum may exceed the limitation as a result of having to pay

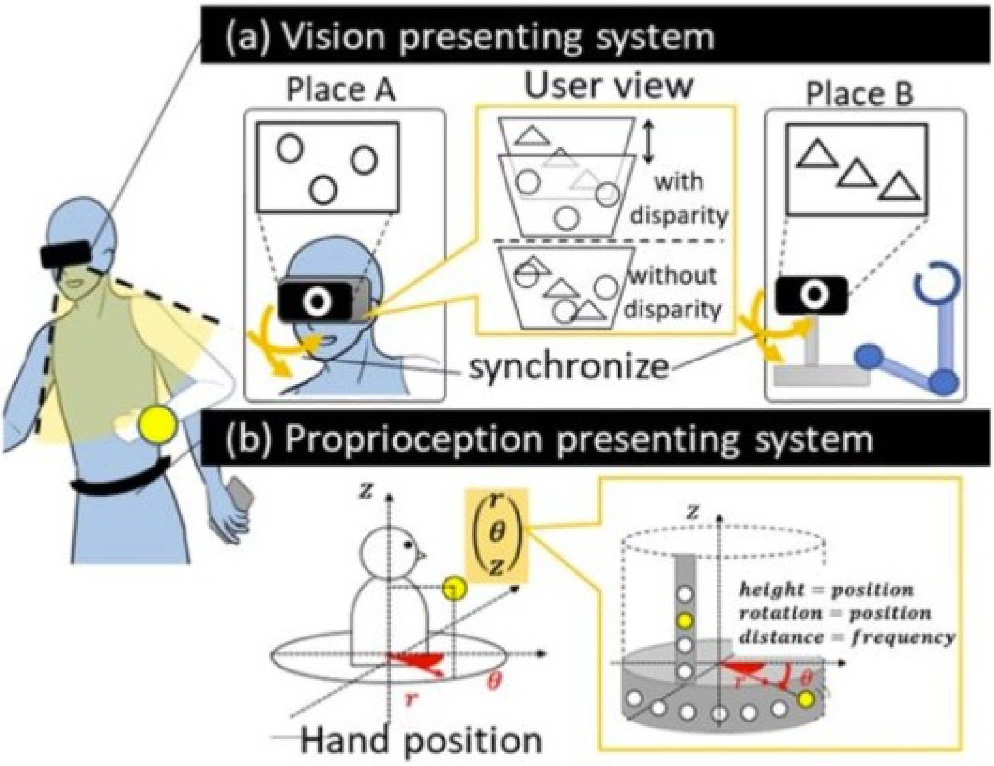


Fig. 37 Structure of dual-presence system

attention to both the environmental images in the subtask and the information in the FB, and the dual task may collapse. This is especially in systems where the user has to process information passively, such as FB systems and concurrent vision presentation systems, where the amount of information input to the user and its processing load should be examined. Therefore, in the next section, we will investigate the effect of disparity in concurrent vision presentation systems and the performance of dual-tasking when it is used simultaneously with FB systems.

4.3 Evaluation

The purpose of this experiment is to clarify the effect of disparity in the concurrent vision presentation system and the effect of position feedback in the concurrent proprioception presentation system on attention distribution while performing concurrent tasks. The usability of the proposed interface is verified by measuring work efficiency and through subjective evaluation.

We hypothesize the impact of binocular disparity and vibrotactile feedback in dual-presence tasks as follows.

- H1: Binocular disparity is effective for distinguishing information of both the current and remote environments within a superimposed field of vision, and assists with easily switching attention between the two environments.
- H2: Somatosensory feedback (FB) information is effective for determining detached body state without relying on visual information; it assists with allocating attention

4.3.1 Overview

Subjects performed the dual-presence task at the current location where their natural body is at, and at the remote location where their detached arm is. Ideally, the experiment should be conducted with several types of tasks in order to avoid any dependency of the result on task contents. However, as the first step of the basic evaluation of disparity and FB, the intent was to verify both hypotheses using one task. This decision was based on the need to first focus on assessing if the subjects would be able to perform the task according to the following aspects.

a) Distinguish between information belonging to the current and remote environments. In addition, respond to a sudden event originating in an environment that they are not currently focused on.
b) Continue part of a task without using visual information if they know or are aware, by other means, of the position or posture of the detached arm.

In order to satisfy the above conditions, we set up the main task and subtasks as follows. The main task is a continuous button-pressing task in which the user operates the detached arm and presses the button indicated as the target. The subtask is an intermittent block-collecting task in which subjects use their natural arms to collect wooden blocks of the color indicated by the color marker only if the marker is visible in the current environment. Subjects perform the main task and the subtask as a synchronous task for 3 minutes. The following four experimental conditions were set for all subjects.

A) With disparity/with FB
B) With disparity/without FB
C) Without disparity/with FB
D) Without parallax/without FB

4.3.2 Main task setting

The main task consists of pushing a button using the detached arm; Fig. 38 shows the environment. Two poles are set up in front of the test bed, each with a robot arm and a camera that provides environment information. The position of a camera against the detached arm was determined from the position of the head against the shoulder of an average adult [78], and the camera angle is always synchronized with the subject's head angle by the servo motor. The detached arm has a length of about 60 cm in accordance with the average arm length of an adult [78], and has two degrees of freedom (i.e., yaw and pitch) as shown in Fig. 38(c). Four numbered buttons are arranged on the desk; the detached arm can reach all of them. The hardware configuration of the detached arm supports for simplicity two degrees of freedom; complex operation and movement have the potential to introduce extraneous variables and may potentially distract from any accurate discussion of the validity of the proposed interface.

After the starting cue of the experiment is given, a random question number is displayed on the 7-segment LED near the second button; test subjects will then operate the detached arm and push the button corresponding to the question number. The subject controls the detached arm using the right and left foot pedals located at the natural body side. There are several conventional studies regarding the control method of SRL as we referred in previous section, but we chose to use feet in this experiment due to avoid using body parts that were already used for receiving information of detached body. Pushing either the left or the right pedal will rotate the detached arm within the yaw axis, while pushing both pedals at the same time will lower the arm in the pitch axis. At this time, if there is a button just below the hand of the detached arm, it can be pushed. When the correct button is pushed, the next random question number is displayed on the LED; this completes a cycle or one trial. Subjects have to repeat this trial continuously until the ending cue of the experiment is given. The data recorded for the main task are the times required to perform a trial, and the number of times the left and right pedals are pushed before

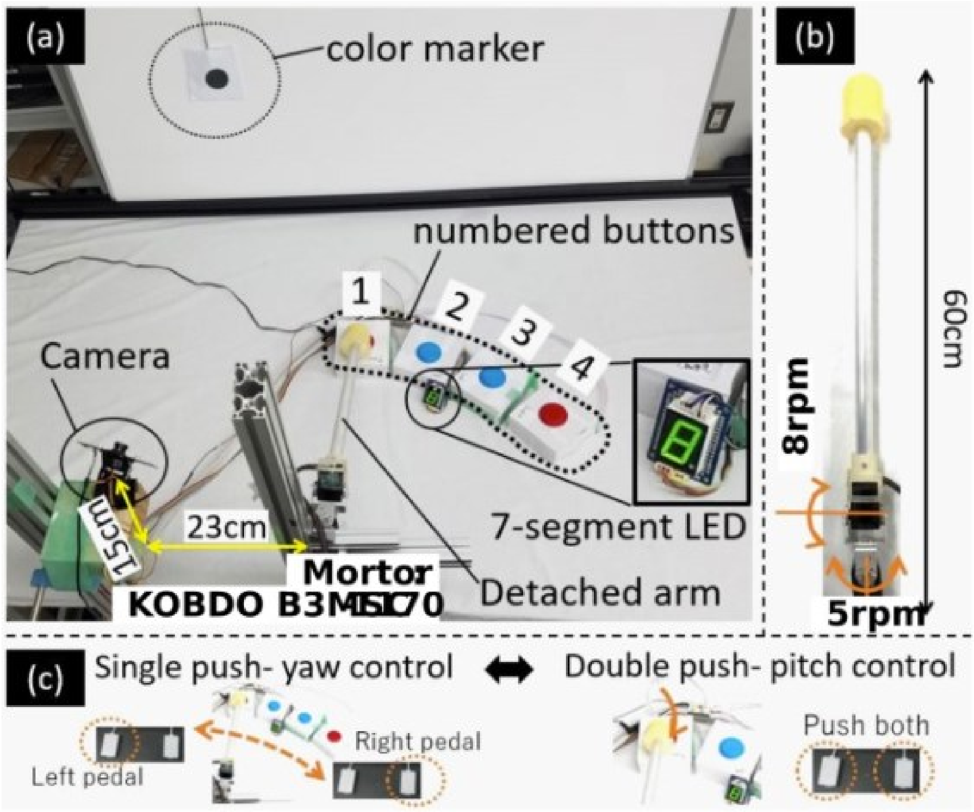


Fig. 38 Overview of experiment setting

the correct button is pushed, again within a single trial.

4.3.3 Sub task setting

The sub task is a block collection task performed with natural arms; Fig. 39 shows its environment. Subjects sit on a chair at the designated position in front of the desk. There are 3 colored buttons, an empty tray, and a bowl with 12 cubic wooden blocks on the desk. All blocks are put with the surface, which has the color marker (red, blue, black) facing down. The white wall is at both the current and remote task areas, and the color indicator can be shown at any position on this wall, as shown in Fig. 38(a) and Fig. 39(a).

After the starting cue of the experiment is given, the color indicator is presented for one second, with random timing, on the white wall in both current and remote

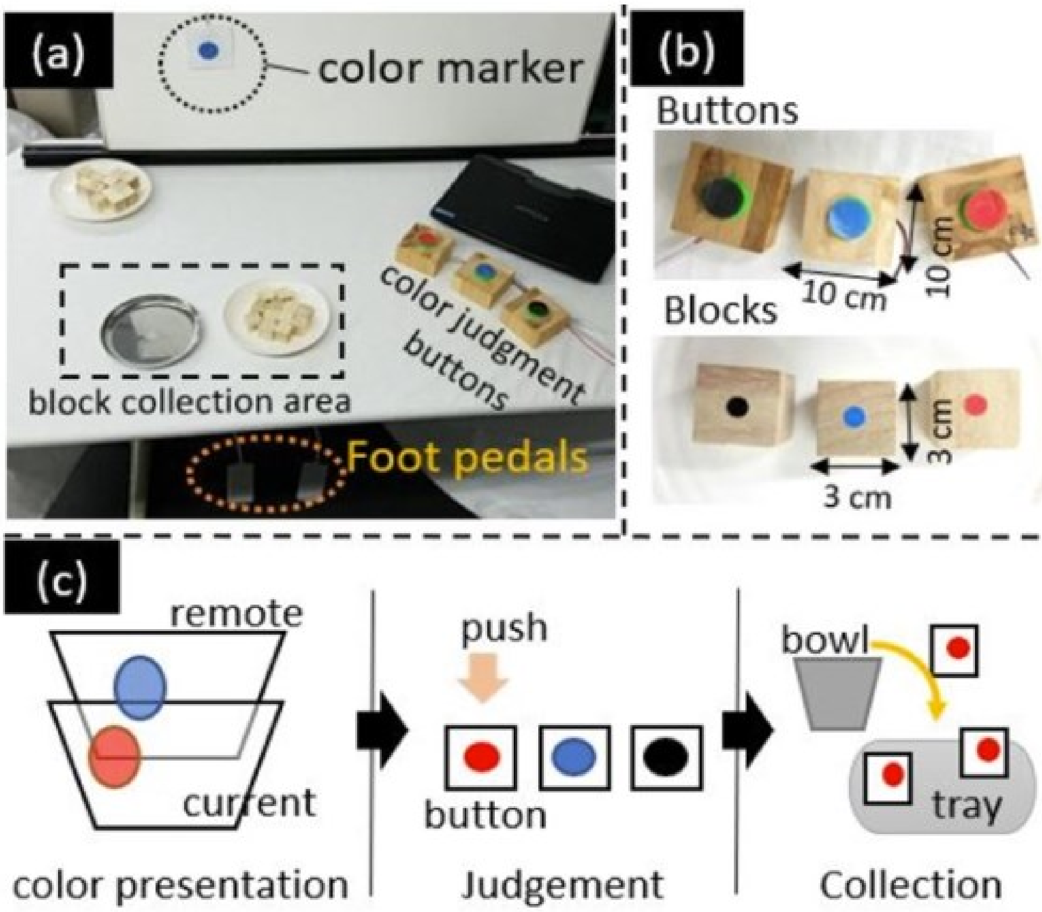


Fig. 39 Settings of main task and sub task

environments, at the same time. When subjects notice the indicator being presented, they judge which color is being displayed in the current environment, push the color button associated with that color, collect blocks of the same color from the bowl, and move them to the tray. The trial ends when subjects push the button again after they finish collecting four blocks of the designated color. The data recorded for the sub tasks are the rates of correct answers given for judgment of color, and the times required for completing a trial.

4.3.4 Interface setting

Fig. 40 shows a system configuration of the interface used in this experiment. VIVE [112] was used for the immersive HMD that presents images of the environment, and the display system was built by Unity [80]. The distance of two image layers was set to 3 m and 50 m as measured from the user's eyes; one layer is within the range where binocular disparity is in effect [113], while the other is sufficiently distant from this effective range. In conditions without binocular disparity, the distance of both image layers was set to 50 m. Since the detached arm has two degrees of freedom, the yaw angle is represented by vibration position and the pitch angle is

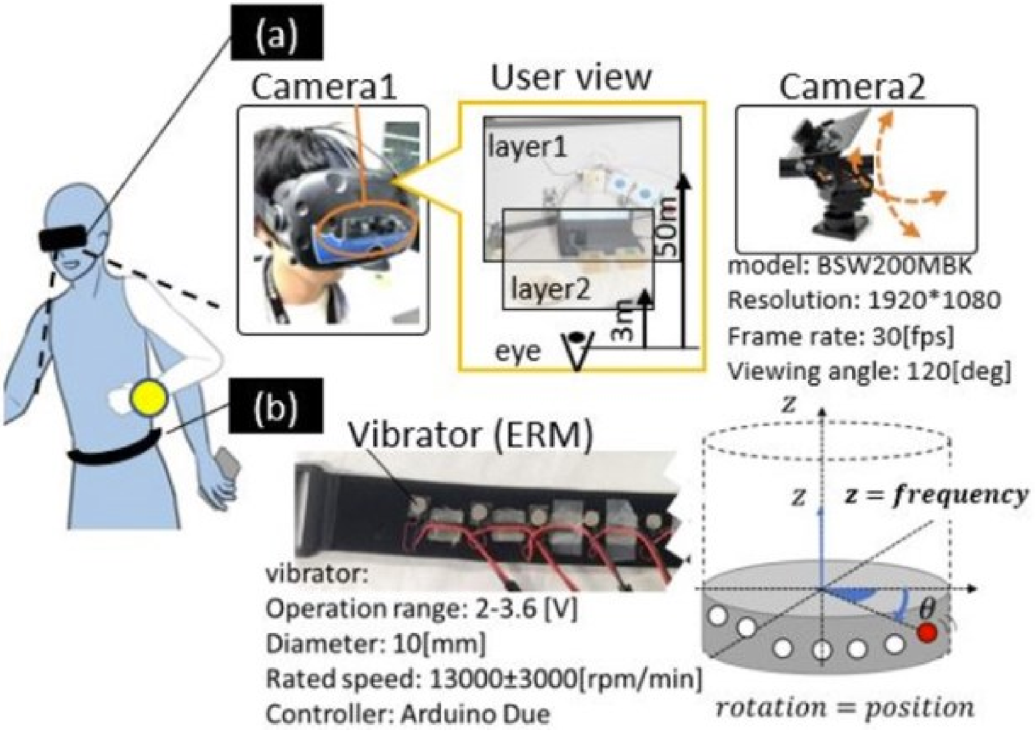


Fig. 40 Interface setting of concurrent vision system and FB system

represented by vibration frequency in the feedback belt as shown in Fig. 40(b). This feedback belt is changed from Fig. 37(b) for representing two-dimensional information. Although the feedback belt is worn over thin clothes, all subjects are questioned and asked to confirm via conversation whether if they can identify the associated vibrations for all vibration positions and frequencies. Other system details, such as the model number of cameras, the vibration frequency, and processing frame rate, are shown in Fig. 40. Because we have used the ERM for vibrators, there was a limitation that we couldn't design vibration frequency and magnitude separately in this experiment.

4.3.5 Procedure

Before the experiment, subjects were given sufficient practice time to perform each task independently and then concurrently. The experiment was conducted for 3 min per each term, and subjects were intermittently directed to perform the sub task while continuing with the main task as much as possible during the term. Subjects performed two terms for each of the experimental conditions A) to D) as mentioned in section A, and the order of the conditions was random for every subject. The number of subjects was 12 and all of them were healthy adults in their 20 s (11 males and 1 female of ages 21-24, mean age 22.3 years, SD 1.23); none of them had any experience using SRLs within daily life. After finishing all conditions, we conducted subjective evaluations by NASA-TLX and a questionnaire using a 7-step Likert scale as a usability evaluation of the system. The contents of the questionnaire are shown in Table III, Q1 and Q2 were related to attention distribution based on two hypotheses, and Q3 and Q4 to survey user impressions of the proposed system and its concept of dual-presence task. Since these were set as the unique scale value,

Table III Contents of questionnaires for dual-presence system evaluation

No.	Category	Questionnaire
Q1	Switching	I could switch my attention between two tasks easily.
Q2	Allocation	I could continue main task easily even when perform sub task.
Q3	Efficiency	I could perform dual-presence task efficiently.
Q4	Dual-presence	I could feel I am at two places at a time.

exploratory factor analysis (EFA) was conducted and Cronbach's α was also calculated, to verify its reliability especially when discussing the overall usability of the interface. Other variables in this experiment design were set as follows. In H1, we measured the effectiveness of disparity in terms of rates of correct answers given for judgment of color, and easiness of attention switching can be discussed by the times required for completing a sub task. In H2, we measured the effectiveness of FB in terms of the time required for a main task cycle and the number of pedals pushing. The effect on attention allocation can be discussed by time required for a main task and a sub task.

4.4 Result and discussion

We conducted two-way repeated measures ANOVA (2 with/without disparity x 2 with/without FB) for all the quantitative results. Multiple comparisons with Bonferroni methods were also used as shown in Fig. 42 to Fig. 44. As a result, the interaction of the disparity and FB was significant in Fig. 42(a) with $F(1, 11) = 8.38$, $p = 0.015$ and in Fig. 42(b) with $F(1, 11) = 5.21$, $p = 0.043$. Regarding the questionnaire, the EFA for the scale supported a single factor structure, with items 1 to 4 loading in factor 1 (respective loads = 0.42, 0.81, 0.74, 0.86). Cronbach's alpha for the whole scale was of 0.79 (minimum corrected item-total correlation = 0.39).

4.4.1 Results and Discussion of the Disparity

Fig. 42(a) shows the correct answer rate of color judgment in the sub task. Regardless of FB condition, the main effect of disparity on the correct answer rate of a sub task was significant with $MD = 2.31$, $F(1, 11) = 53.72$ and $p < 0.001$. This result suggests that disparity is effective in helping with the identification of elements within two superimposed environments in this experiment. This is also suggested by the result of the subjective evaluation Q1 (attention switching) shown in Fig. 43. The score of Wilcoxon signed-rank test was significantly improved in conditions with disparity compared to conditions without ($MD = 1.75$, $Z = 2.19$, $p = 0.028$). These results support and prove H1. However, the practical effects of disparity with respect to work efficiency needs more discussion, because the observed numerical differences

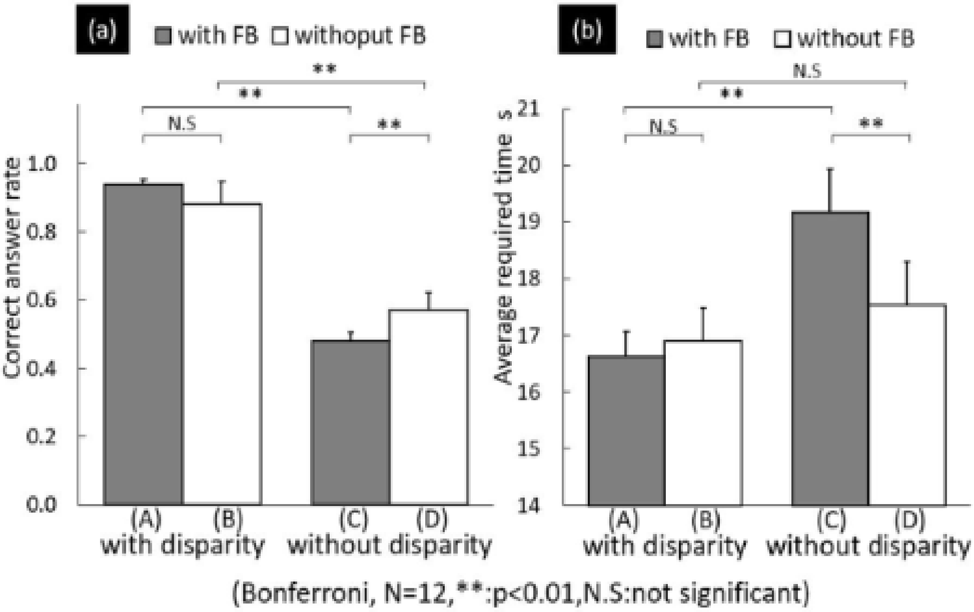


Fig. 42 Results of the subtask

(a) Correct answer rate of color judgment. (b) Average required time per trial.

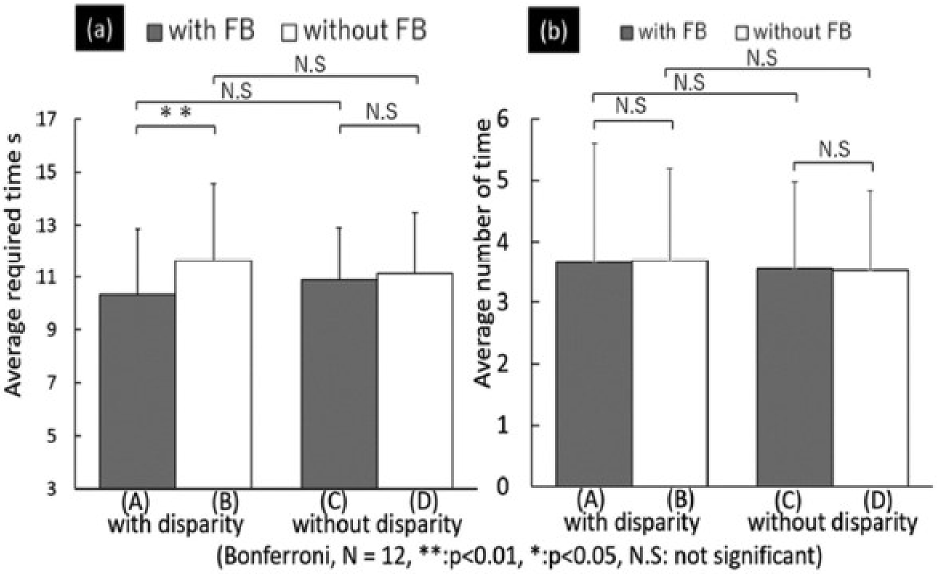


Fig. 41 Results of the main task

(a) Average required time per trial. (b) Average number of times subject has pushed foot pedals per trial.

in work efficiency are not particularly significant. Fig. 41(a) shows the average required time of each trial in the main task, and Fig. 42(b) shows the average required time of each trial in the sub task. There was no significant difference at the level of 0.05 between conditions with and without disparity in both indexes when there was no FB. However, the subjective evaluation Q3 (work efficiency) in Fig. 43 shows that the subjects felt there was higher work efficiency when there was disparity (MD = 2.00, F(1, 11) = 23.94, p < 0.001). These results indicate that the disparity effect does not appear as a quantitative difference in work efficiency in this experimental setting but appears as a usability difference in attention switching. Therefore, the disparity effect is considered to play an important role in dual-presence tasks that involving switching attention between two places many times (e.g., turning over the pages of a book in the library while writing down its contents in a separate note).

4.4.2 Results and Discussion of the FB

Fig. 41(a) shows the average required time of each trial in the main task. When there was disparity present in the interface, the required time was significantly reduced in conditions with FB compared to conditions without FB (MD=1.31, F(1, 11)=3.66, p=0.001). In addition, in the subjective evaluationQ2 (attention allocation) in Fig. 43, the score of Wilcoxon signed-rank test was significantly improved in conditions with FB compared to conditions without FB (MD = 2.42, Z = 2.93, p =

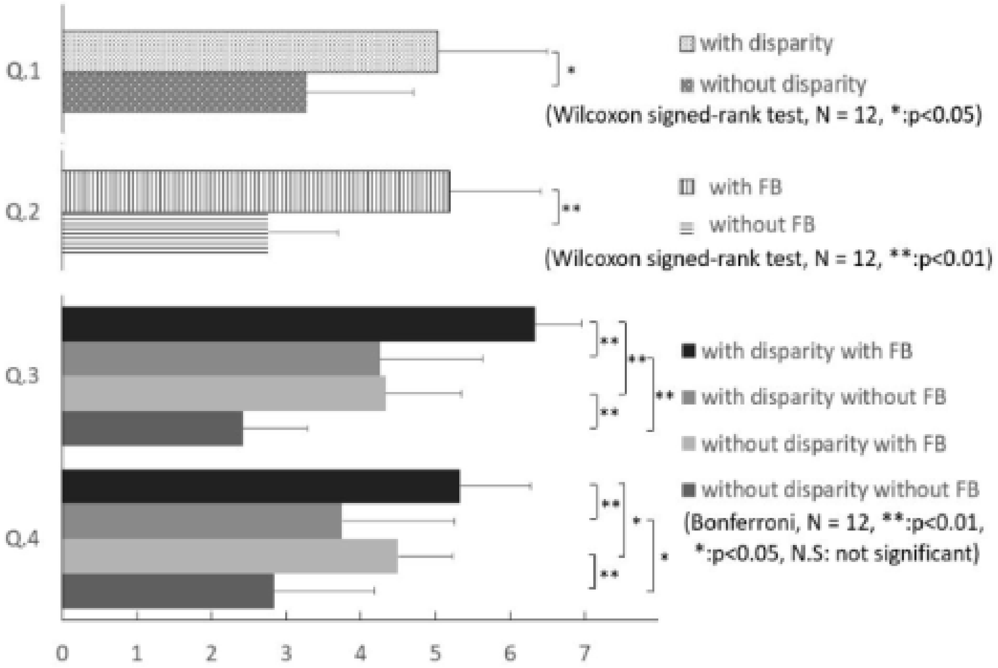


Fig. 43 Results of subjective evaluation

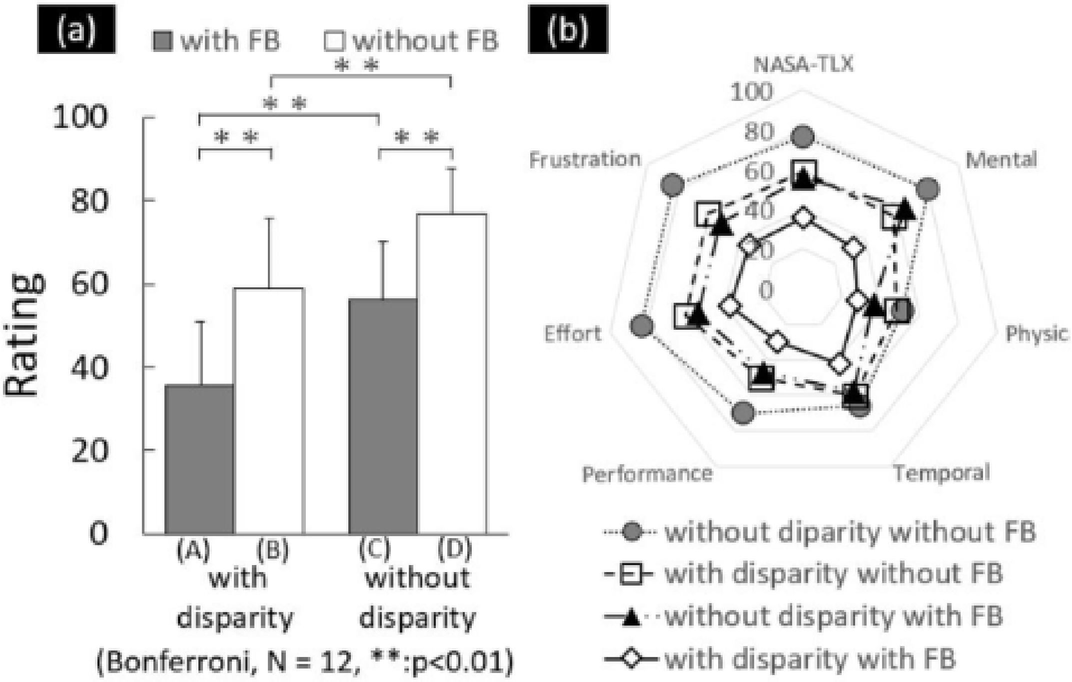


Fig. 44 Results of Nasa-TLX

(a) Overall score of each condition. (b) Every index score of each condition.

0.003). Therefore, these results suggest that FB is effective in knowing the state of the detached arm and in reallocating attention to each task with optimal timing. In addition, many subjects looked at and confirmed the progress of the main task at unnecessary times during the performance of the sub task in conditions without FB. These results partially prove H2; however, H2was rejected when there was no disparity in the interface. As shown in Fig. 41(a), there was no significant difference at the level of 0.05 in time required between conditions with FB and without FB when there was no disparity. Surprisingly, the correct answer rate of a sub task shown in Fig. 42(a) was significantly reduced by FB when there was no disparity (MD = 0.54, F(1, 11) = 2.94, p = 0.008). FB seems to require a certain amount of attention for its information processing. Indeed, in case of the absence of disparity, the subject would have difficulties correctly identifying the environment related to the FB, sometimes mistaking it. Moreover, the additional focus necessary for the comprehension of the FB information would be taking attention away from the main and sub tasks. Hence, H2 is partially rejected. When a dual-presence task requires significant attention, e.g., when performing a dangerous task such as handling a knife, or when it is difficult to identify the environment related to the FB such as no disparity in the interface.

4.4.3 Optimal Combination of Disparity and FB

In this experiment, we discussed the effects of disparity and FB on attention switching and allocation as parameters of the interface for dual-presence tasks. From the viewpoint of usability, both disparity and FB are necessary for the interface. Disparity helps the user to identify elements between the two environments and to switch their attention between them, while FB helps the user to determine the condition of two bodies without using vision and to reallocate his or her attention when necessary. Since disparity reduces the amount of attention required for identifying and switching environments, it is effective to use disparity together with FB requiring varying amounts of attention for information processing in the case of normal dual-presence tasks. The results of the subjective evaluation in Fig. 43 and NASA-TLX in Fig. 44 showed the highest usability in almost all indices when the interface with combination of disparity and FB were used. However, it is preferable that disparity and FB are used properly according to the contents of dual-presence task, based on their characteristics clarified by this experiment. For example, when two environments are very similar and users are required to identify their workplace accurately, disparity would be more important than FB. On the other hand, when there is no sudden visual event and continuing a particular operation is important (e.g., stirring a pot), FB information would be more important for the interface. The required amount of attention for disparity and FB should be further discussed from a cognitive science standpoint. Wilson & Golonka [114] suggested that we have to analyze the information resources that subjects use when discussing embodied cognition. In the future study, it is important to analyze how information resources are assigned including processing the disparity and FB through various kinds of task situations.

4.5 Chapter discussion

Dual-presence tasks enable the execution of concurrent tasks in two distant locations. In this section, we propose an information presentation interface for the dual-presence task, verified the effects of disparity in the concurrent vision presentation system, and the effect of FB in concurrent proprioception presentation system for the free distribution of user attention. The results suggest that disparity is effective for environment identification and attention switching, while FB is effective for optimal attention allocation.

Now we discuss issue (3) "Dual-presence increases the amount of environmental information that needs to be processed, which takes up a large amount of attention and makes it difficult to perform efficient dual-presence task" from the development and verification of the concurrent vision presenting system. The difference in whether or not to use disparity when presenting image information of the two environments can be considered not only in terms of the ease of visual identification of the images, but also in terms of whether or not the information was weighted for the user. For example, when there was no disparity, the two images are always presented equally, and the users cannot tell which side they are on. This can be explained by the fact in the discussion of the experiment that some users were reported to have mistakenly reached for objects in the remote environment. On the other hand, when there was disparity, users were able to properly identify which environment they were currently in, and were able to pay greater attention to the task as needed depending on the situation. In terms of the strength of the sense of "dual-presence", a state in which the users do not know which environment they are in is considered to be a strong sense of dual-presence in two environments. On the contrary, a state in which the users know exactly which task they are focusing on will bring about a sense of being present at one point while being thinly present at the other, and the sense of dual-presence will be weaker. If we consider this in the design of the current system, it would be desirable to have no disparity if the strength of the sense of dual-presence is important. If the performance of the dual task is important, it would be desirable to have a clearer sense of where users are paying attention than the sense of dual-presence. Therefore, as a design theory for a SRL for dual-presence tasks, it suggested that to create a situation where the user can focus on mainly one environment at a time while paying a low level of attention to the other environment, rather than presenting information from two environments equally to increase the sense of dual-presence.

This discussion also has implications for the design of FB systems. In the current experiment, FB contributed to the distribution of attention to the two tasks, which may be due to the difference in the type of FB from the natural body and from the Detachable body, and the subjects did not confuse these two. When we create a FB system that can make the state of the SRL feel the same as that of a natural body, or when we handle more than two SRLs, there may be confusion in the association between FB information and task information as in the case of environmental images. In this case, it is necessary to come up with an idea to make the information stronger or weaker. For example, the system determines which body the user is currently paying a lot of attention to from the environmental image where the eyes are focused, and then weaken the FB from other bodies.

Chapter 5: Discussion

This chapter discusses the contributions, limitations of this thesis through the development and experiment of the operation system, the FB system, and the dual-presence system. In addition, this chapter also discuss new research questions regarding the design theory of the SRL based on the contribution of this thesis.

5.1 Contribution

The final goal of this research is to develop the SRL system for dual-presence tasks. In order to achieve this, we proposed the concept of a Detachable body, which can be attached to or detached from the natural body, in contrast to conventional human augmentation systems that have been proposed for wearable use. The main research question was how to design an SRL system for dual-presence task. This is a very general question, and there are many possible approaches. In this thesis, we started from the point that humans are not good at performing dual tasks due to their cognitive characteristics. We set up three issues in terms of human attention when trying to perform a dual-presence task, and conducted experiments on each of them, suggesting three contributions to the design theory of the SRL.

First, through the development of an intermittent operation system using a face vector, it suggested that there is a trade-off between reducing instruction errors and reducing the required attention. As a result, the design theory was suggested that it would be better to focus on reducing the attentional resources consumed rather than the accuracy of the instructions, and absorb the errors by other design elements such as hardware mechanism.

Second, through the development of a FB system of hand's position of the SRL using the vibration array belt, in suggested that the introduction of partial automatic control may interfere with proper attention allocation because the user may have to repeatedly look at the SRL to check it. In order to prevent this, the design theory was suggested that to have a FB system which inform the posture or working state of the SRL is effective to reduce the attentional resources required to the SRL, especially when there is the part of automation in the operation method.

Third, through the development of a dual-presence system with superimposing two transparent images using the disparity effect, it suggested that a strong sense of simultaneous presence and equal input of information from each environment may make it difficult to switch attention. As a result, the design theory was suggested that to create a situation where the user can focus on mainly one environment at a time while paying a low level of attention to the other environment, rather than presenting information from two environments equally to increase the sense of dual-presence.

5.2 Limitation

As the interfaces and verification tests developed in this study have some prerequisites, the scope of the above contributions and considerations is subject to some limitations. In this section we discuss the most important of these: task dependency and time dependency.

5.2.1 Limitation of task dependency

In this study, we have developed three interfaces for a dual-presence task and tested their usability in a dual-presence task situation, where all the main tasks and sub tasks were different and there was only one of each kind of task. The reason why each task was set was to reflect the target situation of the interface verification as described in each experimental design, but it is unclear whether the same results and tendency would be seen if the task contents were changed. However, it is unclear whether the same results and trends would be seen if the task contents were changed. Although there is no detailed analysis of the tasks to be set in such cases in the past study, some properties can be summarized from the tasks that have been set in the design of the SRLs for the current work.

- Physical task, cognitive task
  Physical tasks are tasks that focus on the placement and manipulation of objects by moving the joints of the body such as limbs. For example, the task of during the verification of a face vector system which discriminating the shape of a block with the sense of touch and placing it, or the task of during the usability

verification of a FB system which measuring water as quickly and accurately as possible, are considered to classified into this category. On the other hand, cognitive tasks are tasks that focus on cognitive activities such as calculation and stimulus response rather than body movement and object work. Examples of such tasks include the mental arithmetic task performed during the verification of the accuracy of the FB system, and the task of pressing the color buttons presented in one's environment as quickly as possible during a part of the verification of the dual-presence system.

- High attention task, low attention task
  A high attention task is a task that requires a lot of attention. For example, a dangerous task such as cutting vegetables with a knife, an unpleasant task such as a weak electric current flowing when touching a wall while walking through a narrow passage, and a precise task such as stacking 1mm-wide coins vertically, are considered to classified into this category. On the other hand, low-attention tasks are the opposite of these, and can be set up by, for example, repeating simple trajectory drawing incessantly, or increasing the range of hit judgment in pointing tasks.

- Intermittent task, continuous task
  An intermittent task is a task that does not require constant attention during the task, but requires intervention at regular intervals or as needed. For example, a task that occurs every 10 seconds, such as breaking a balloon or turning down the heat when a pot starts to boil, can be considered as an intermittent task. A continuous task, on the other hand, is a task that requires constant execution and intervention. For example, a task that requires the user to keep tracking a moving target with his or her eyes or hands.

- Task with modality overlapping, without modality overlapping
  This is a classification based on the relationship between the main task and sub task set up in a dual task. A task with overlapping modalities is one in which, for example, the main task is to track a moving target while the sub task is to read out the displayed text. In this example, both the main task and the sub task require the use of vision, so there is an overlap of modalities. The dual task becomes a "macroscopic" dual task where the two tasks are not completely concurrent, but are performed by switching between them in detail. On the other

hand, a task that does not overlap modalities is the opposite. For example, as the situation of verifying face vectors, only tactile perception is used in the main task, while vision and face orientation are used in the sub task, which logically means that a complete concurrent task is possible.

In this way, tasks can be set in various ways depending on their nature, and the experiments discussed in this paper need to be re-examined under task settings with different characteristics. This will allow us to further investigate the range of applicability of the properties of each system revealed by the present experiments.

In addition, setting one continuous task as the main task to be performed by the natural body in parallel with the operation of the SRL, would allow for the evaluation of the quantitative and temporal characteristics of the attention required by each interface. For example, if we consider the task of following a moving target with the hand as a continuous task as shown in Fig. 45, the performance of this task can be output as a temporal change in the distance between the subject's hand and the target. This become to the standard performance in the single-task state where all the attention is directed to the following task, as shown in Fig. 45. By comparing this to when performing the task in the dual task state with the operation of the SRL, we can evaluate at what timing and to what extent the attention was taken.

Also, setting one common task as the main task would allow for the comparison of these elements across systems. For example, when comparing face orientation and eye gaze as modalities for pointing at an object in a operation interface, it becomes clear that the time spent in eye gaze is shorter, but the level of attention required in face orientation is smaller. This comparison can also be applied to other system elements of the interface. For example, if the performance in the single state of the following task is 100, and the performance is 50 when it is done at the same time as the FB system is used, and 30 when it is done at the same time as pointing, because it can be seen that 50 of the attention is taken up by FB and 70 by pointing. As a result of this example, a design theory could be to turn off FB when pointing so that the limitation of attention resources is not exceeded.

5.2.2 Limitation of time dependency

In the experiments conducted in this thesis, the subjects were given some practice time to use the interface device before the data collection, but these were all 5 to 10 minutes to understand how the device works and to reduce the variability in the performance during the experiment. The overall duration of the experiment, including data measurement, was kept to less than an hour in consideration of the subject's fatigue and loss of concentration. In other words, we have not been able to go into the characteristics of attention when the device is used for longer than an hour.

It is thought that the amount of attention required to maintain performance while executing a certain task differs between those who are proficient in the task and those who are not. For example, for a novice driver who has just obtained a car license, driving requires a great deal of attention. However, as the driver gradually becomes proficient and accustomed to driving, he or she can afford to do other tasks at the same time, such as talking with other people in the car or adjusting the air conditioning. This is thought to be the result of a decrease in the amount of attention devoted to driving as a result of mastery of the driving task, and as a result, attention can be diverted to other tasks. A similar situation can be expected when using the SRL for a long period. After the performance in the use of the operation system and the FB system has stabilized, it is possible that the attention devoted to these systems will decrease as the user continues to use them for several hours, days, or even years to become proficient (Fig. 46). Indeed, some references show that training

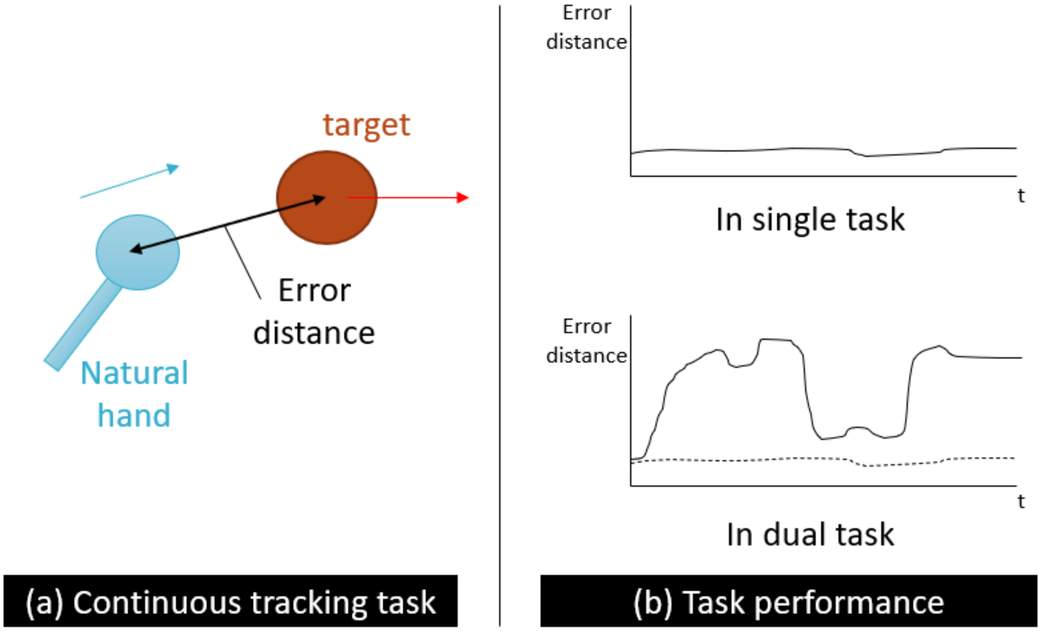


Fig. 45 The model of continuous tracking task

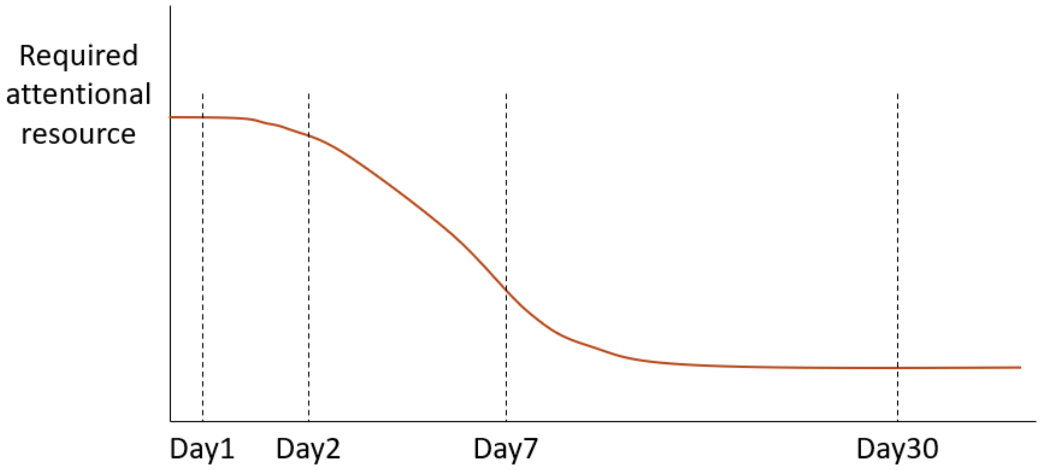


Fig. 46 Model of required attentional resource with long term use

of dual task can be improve its performance [115] [116]. Therefore, the experiments discussed and the design theories in this thesis are useful in the very initial stages of introducing SRLs, but it is necessary to re-evaluate the usability of each system if it is to be used for a long period of time. For example, in the design of the prototype of the FB system, we decided to use only the three-dimensional position of the hand as simple and limited information as possible so that interpreting the FB information itself would not be a burden on attentional resources. However, if the attentional resources consumed for interpreting the FB information become small after several days of use as shown in Fig. 46, it is possible to consider putting more information on the FB system than the current design, such as the three-dimensional position of the elbow joint or the point of contact with the environment.

On the other hand, the investigation of attentional characteristics with time on the instantaneous scale of one second or one millisecond is also a limitation that we have not been able to go into in this thesis. For example, the operation interface using face vectors was proposed as an intermittent instruction that requires only instantaneous attention, as opposed to the conventional master-slave method that requires continuous attention. However, it is difficult to give a specific definition to the term "intermittent," and it is not possible to say whether an instruction that ends in 0.5 seconds can be considered intermittent or whether an instruction that ends within 3 seconds can be considered intermittent. Also, as mentioned in the previous section, even if the time required for an instruction is the same, if the level of attention required for that instruction is different, it is likely to affect the dual-presence task performance. For example, as one-second operation, user can continue with the other task if the operation is as simple as pushing a button in. However, as same one-second operation, if the operation is as precise as turning a dial exactly 1mm, the other task will have to be interrupted completely.

Based on these discussions, we propose a concept of "attentional product", which is the product of "time required for attention" and "required attention level," to quantitatively discuss the characteristics of human attention to the SRL during dual tasks. Fig. 47 shows this concept of the attentional product, which can be tested by making various hypotheses from the three perspectives of the time axis direction, the attention level direction, and the area calculated as the product of these two axis. For example, to examine the characteristics of the time axis direction, we can measure the performance of the main task by changing the duration of the sub task that requires the same level of attention for 1 second, 3 seconds, 5 seconds, etc., as shown in Fig. 47. If the results show that a 3-second or 5-second instruction completely disrupts the main task, but a 1-second instruction does not completely disrupt the main task, we can obtain a design theory that allows us to improve the performance of the dual task by, for example, completing the instruction within 1 second as an intermittent operation. To examine the characteristics of the attention level direction, we compare the operation method that require different attention levels for the same amount of time, as shown in Fig. 47. This is similar to the discussion of modality comparison in the previous section. In addition, we need to investigate the possibility that these two characteristics are not independent, but that their product influences task performance. This possibility can be examined, for

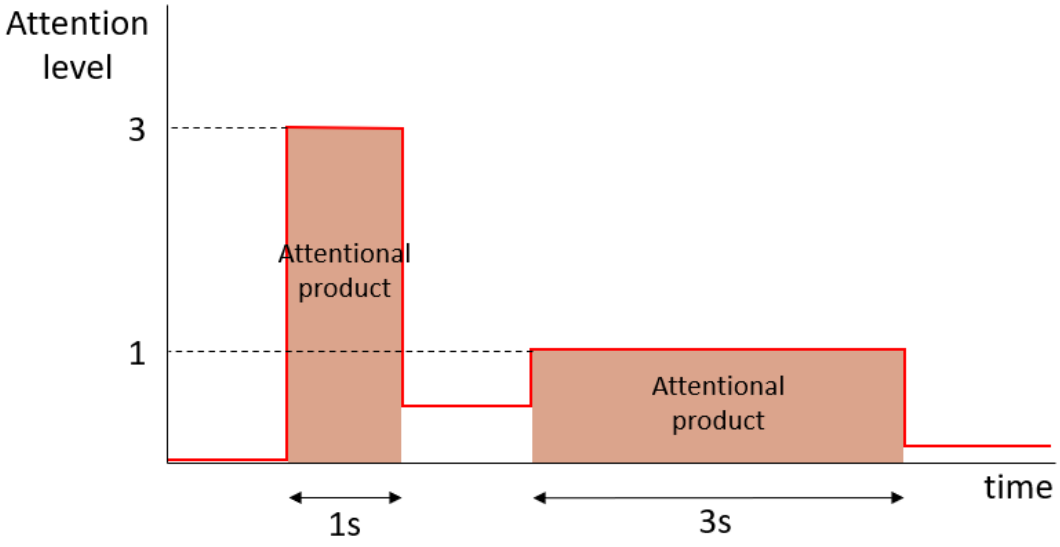


Fig. 47 The concept of attentional product

example, by measuring the performance of the main task when a task with attention level 1 is continued for 3 seconds and when a task with attention level 3 is continued for 1 second, as shown in Fig. 47. If result can be observed that these two are equivalent in some cases, it may draw a new design theory when selecting a operation method or FB method. For example, when using a modality with a high attention level, the information exchange should be completed in as short a time as possible. On the other hand, in the case where a long period of information input or output is unavoidable, it is recommended to select a modality or transmission method with a low attention level.

5.3 Next research questions

In this paper, we have discussed three issues that arise when performing tasks while using a SRL from the perspective of attention allotment. Based on the above contributions and limitations, we propose two new research topics that should be approached in the future. One is to establish a design theory of the SRL when expanding from a dual-presence task to a multi-presence task, and the other is to investigate the effects of inducing "embodiment" of the SRL on attention allocation.

5.3.1 Question to Multi-presence task

Regarding the expansion to multi-presence tasks, the question is how design the SRL system for efficient multi-presence task. This takes over the issues of dual-presence tasks that we have approached in this thesis, but raises new issues due to the increase in the number of tasks and locations. For example, we discussed the possibility that dual-presence tasks may not be viable due to the additional environmental information that must be processed as opposed to single-presence dual tasks, which consumes attentional resources. When the task becomes multi-presence, the user has to process information on multiple bodies and multiple environments in each location at the same time, and the load on attentional resources is expected to become higher and higher as the number of tasks increases. Some studies have also indicated that the human brain is biologically incapable of performing more than three tasks [117]. On the other hand, when we are performing two different tasks A and B, for example, we can perform task A1, then task B1, then task A2, then task B2, and so on. It is known that the performance of dual task can be improved if the executor knows in advance the order and timing of the two tasks [118]. In such a case, even if the tasks are different, the two tasks might be recognized by the executor as one continuous task, as if they were a single task. The same thing is expected to happen when processing three or more multiple tasks. In other words, the users pay a great deal of attention to the main task they are currently performing, and all the remaining tasks, no matter how many they are, are taken as one chunk. When switching tasks, the users select the desired one from the "rest of tasks" and shift the main attention to it, and the task to which the users have been paying attention is integrated into the "rest of tasks. Thus, by viewing multitasking as a dual task consisting of the "main task" and the "remaining task group," the design theory for dual tasking that has been approached in this thesis can be applied. However, in multitasking, the process of searching for the next task to shift attention to from among the "remaining tasks" is newly added. This is expected to become more pronounced as the number of tasks increases, and the following issue can be set.

- [Issue 4]: Task searching process consumes a large amount of attention and prevent the efficient multi-presence task, especially the number of tasks become larger.

We will discuss this issue in more detail through the interface design for multi-presence tasks in Chapter 6.

5.3.2 Question to SRL's embodiment

At the beginning of Chapter 1.3, we mentioned that there are two major questions in the development of a Detachable body: One is "How can we design a system that can perform dual-presence tasks?" The other is "How can we design a system that feels like our body when we wear it or detach it?" The three issues, system development, and experiments in this thesis are all focused on the former question. In this section, we will discuss the latter question in more detail based on the contributions obtained in this research.

The question of the embodiment of the SRL can be discussed from two additional perspectives. One is to clarify the specific benefits or effects of inducing embodiment into the SRL, and the other is to clarify the method to create the embodiment feeling to the SRL that have never existed before in the natural body.

5.3.2.1. The benefit of inducing embodiment into the SRL

Although there are many augmented body applications being developed for the purpose of work assistance, there is still no clear answer to the question of why they need to be felt as a "body" and not just a robotic arm. As mentioned in Chapter 1, one advantage of introducing an augmented body that allows users to voluntarily operate it as if it were their own body is that it enables non-task-oriented support for situations that are difficult to handle through full automation, such as daily life. On the other hand, this is simply an advantage of a "wearable personal manipulator," and it is not essential that the user feels the manipulator as if it were his or her own body.

It is possible to think of the difference between feeling the robot arm as one's body or not from the perspective of user experience. For example, there are some tasks in our daily life that we do not want others or unfamiliar systems to perform, such as touching a baby or a pet, or carrying a very expensive item from room to room. For such tasks, even if users get a simple robot arm, they would not want to use it for this purpose, but if it feels like their own body, users will have the option to use it. In this way, it may be beneficial for users to recognize the SRL as part of their own body, thereby expanding the range of tasks that the augmented body system can support. On the other hand, it is difficult to even formulate a clear question about the effect of the presence or absence of the embodiment on task performance and system usability. When we use the term "as if it were our own body," we include vague nuances such as "as if it were our own body, we can control it as we wish" or "as if it were our own body, we can use it with confidence." However, it is difficult to verbalize what exactly is useful.

Given the contributions of this study, now we can start to discuss the benefits of embodiment in this task support in terms of "how does the embodiment affect the user's attention allocation during a dual-presence task?" From this perspective, the following questions can be considered.

- "Does embodiment reduce the required attention?"

In the section on the development of operation systems, we mentioned that there is a trade-off between the accuracy of the operation instructions and the attention required, and suggested that one solution is to absorb the error in the instructions with other design elements such as hardware development. However, if we use our own natural body, we can do some detailed work without devoting too much attention. If there is a possibility that we can pay less attention with maintaining the task performance by feeling the system as our body, then we have a new direction to resolve this trade-off.

- Does embodiment improve the confidence?"

In the section on the development of the FB system, we mentioned that the purpose of FB of the posture information of the augmented body is to reduce the user's anxiety about the system. Also, to prevent the attention required to interpret the FB information itself from affecting the dual task, we limited the amount of FB information: the 3D coordinates of the hand position. However, we are less likely to distrust our own natural body, even when we pay little attention to where our arms are. If there is a possibility that perceiving the SRL as one's own body can improve the confidence, even though the amount of FB information is the same, then a new solution can be considered for reducing distrust in SRL, other than increasing the amount of FB information which risks degrading task performance.

- Does embodiment reduce the switching cost?

In the section on the development of the dual-presence system, we mentioned that the system should be designed so that the focus of the user's attention is clearer than presenting all information flatly. While this method encourages the focus of attention, it also has the possibility of making it difficult to notice changes or errors that occur in the environment to which less attention is currently paid. However, in the case of our own natural body, we can naturally react to someone approaching behind us, even if we are not paying much attention to our own back. If it is possible that perceiving the SRL as one's own body makes it easier to notice changes or errors that occur in the vicinity, even when not much attention is being paid to it, this opens up new possibilities for further reducing the switching costs of dual-presence tasks.

5.3.2.2. The method of inducing embodiment into the SRL

The augmented body is a new body part that human beings have never possessed before. This is different from the case of a patient who has lost a limb due to an accident, and uses a prosthetic hand or leg as a substitute for the natural body, which requires the creation of a new body part and its embodiment. Thus, there are two possible approaches to inducing embodiment in a body part that has never existed before: a bottom-up approach and a top-down approach.

As a bottom-up approach, several conditions are known to induce the embodiment to the object as described in Chapter 3.5: it can be moved voluntarily (agency), it can be felt as one's belongings (ownership), and it is located in the same position as the image of the body part (location). For example, in terms of agency, it has been suggested that synchronizing the manipulation intention with the result can induce an agency in the target object. In this case, if we use the movements of the hands and feet of the natural body to manipulate the SRL like a master-slave system, the embodiment induced in the SRL will not be recognized as a new part of the body, but as a remapping or copy of the existing embodiment of the hands and feet. Therefore, it is desirable to manipulate the SRL and obtain an agency by using a method that can output the manipulation intention while preserving the existing body scheme as much as possible. The same thing can be said about ownership. In the natural body, it is known that ownership can be induced by synchronizing the sensory feedback to oneself with the sensory feedback that can be generated in the object to which embodiment is transferred. For example, when an object touches the fingertips of the SRL, if the tactile sensation is transferred to the fingertips of the natural body, the embodiment induced in the SRL may be a copy of the embodiment of the existing hand. Therefore, it is desirable to perform sensory FB of the SRL using modalities and sites that do not interfere with the natural body senses as much as possible.

We are now in the process of challenging a method to induce agency and ownership to the SRL based on this approach of not interfering with existing body schematics and body sensations as much as possible [119]. As a prototype for this purpose, we constructed a myoelectric control system for inducing agency (Fig. 48(i)) and a force-feedback (FB) device for inducing ownership (Fig. 48(ii)) to move a SRL in a VR environment as shown in the figure. In the myoelectric control system, the timing of the start of rotation of the VR arm was synchronized with the myoelectric potential fluctuation caused by active contraction of the upper trapezius muscle. The trapezius muscle is usually contracted consciously infrequently, and we thought that this would hardly interfere with the embodiment of the existing body scheme. The system is calibrated in advance to set a threshold, and when the muscle potential exceeds the threshold, the VR arm starts to rotate. In the force-feedback FB system, the FB belt, to which three servomotors and four vibration motors are attached, is used by wrapping it around the left upper arm near the shoulder. One servomotor is assigned to each 30 deg of the VR arm. The servo motor rotates its horn according to the

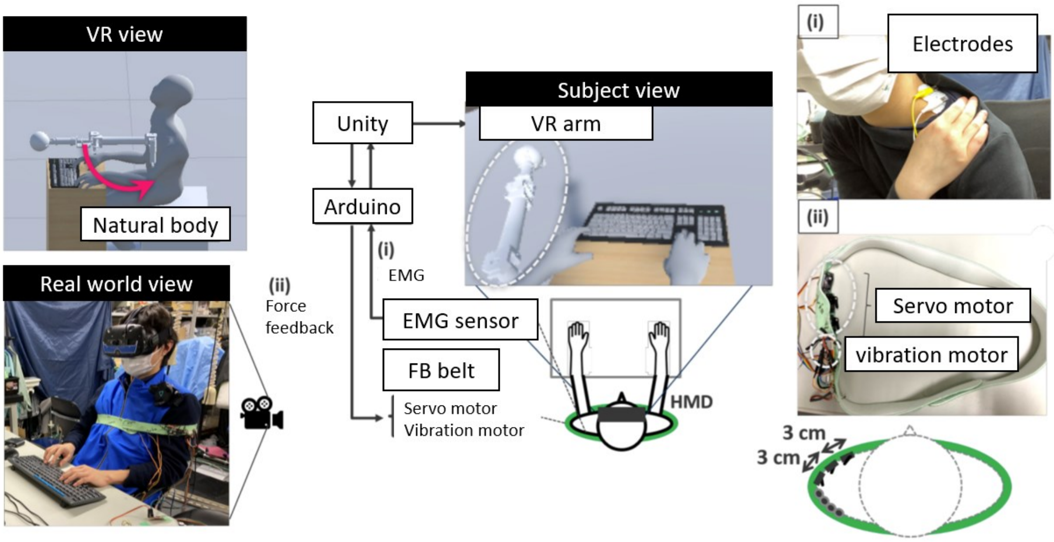


Fig. 48 Setting of embodiment induction interface [119]

direction of the VR arm to present a clamping force to the shoulder, which imitates the movement of the VR arm. In addition, when the VR arm comes in contact with an external object, the vibration motor vibrates simultaneously, and the servo motor corresponding to the direction of the VR arm works further pushing force. We will investigate whether or not embodiment is induced in the SRL when it is operated and FB using such a system. Although it is difficult to directly measure the induction of embodiment in the SRL, subjective evaluation and changes in body width sensation are used as indicators for the induction of embodiment in the natural body. For example, as shown in the Fig. 49, an obstacle is fired from various positions in front of the subject, and the position where the subject feels that the obstacle has hit his or her body, which represent their body width. It considered to change depending on the presence or absence of embodiment to the SRL.

As a top-down approach, let users perform various tasks in the daily life while wearing the SRL, and observe whether there are any changes in their behavior, cognition, or brain activity. In fact, it has been reported that after five days of wearing a sixth finger made by a robotic system, brain activity regions responding to the movements of the sixth finger were newly created in addition to which corresponding to the movements of the normal thumb, index finger, middle finger, ring finger, and little finger [120]. This indicates that the continuous use of the SRL itself may actually cause changes in brain activity and alteration of the body scheme. On the other hand, the behavioral component of how the SRL is used and acted upon to promote such a change is not known. In the aforementioned study, the subjects were only instructed to use the sixth finger as much as possible. There are some behavioral factors considered to influence this transformation of the body image, for example, whether the behavior of moving objects with the SRL had a strong influence or whether the behavior of moving while wearing the SRL so as not to bump into the surroundings had a strong influence. If we can find out what behavioral factors influenced the transformation of these body scheme, we can develop training programs which incorporate these factors to speed up the process of inducing embodiment in the extended body.

We are now in the process of challenging a training field in a VR environment that includes several behavioral elements which considered to be involved with embodiment induction. For example, VR interaction sites such as VRChat [121] often have mirrors in the space, and it has been reported that when the reflection of oneself in the mirror and one's avatar in the VR are synchronized, the sense of body ownership toward the avatar is significantly higher than when they are asynchronous [122]. Thus, the element of looking at the full body view of one's own body with the SRL in a mirror, can be a behavioral element for inducing embodiment. Other studies on the embodiment of tools are also informative. For example, it has been reported that motor learning to use a tool and move to a target quickly and accurately leads to faster target detection around the tool [123]. It is believed that by moving the upper limb quickly and accurately, the brain learns the relationship between motor prediction and sensory feedback, allowing it to take the upper limb as its own body. Therefore, playing a game that requires quick reaching to a target

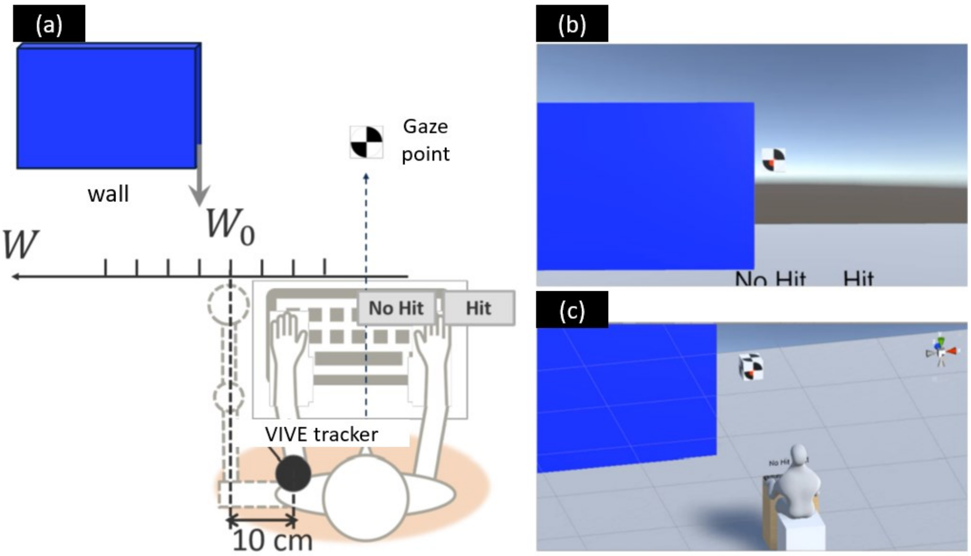


Fig. 49 Example of the environment setting of measuring body width [119]

object using the SRL can be considered as behavioral elements to induce embodiment to the SRL.

Chapter 6: Advanced discussion

This chapter further discusses the application to the multi-presence task, which was taken up as the next research question in Chapter 5, by addressing problem (4), "Task searching process consumes a large amount of attention and prevent the efficient multi-presence task, especially the number of tasks become larger."

6.1 Multi-presence task

The purpose of this thesis was to develop an interface for the dual-presence task, which two different tasks are performed in two distant locations. As the next step, it is expected to expand this interface design for multi-presence tasks, in which the user can perform multiple different tasks simultaneously in multiple locations. In this case, the user has multiple Detachable bodies and places them in several environments to perform concurrent tasks in multiple environments. Some of the body parts placed in the environment may be temporarily unused by the user, or may

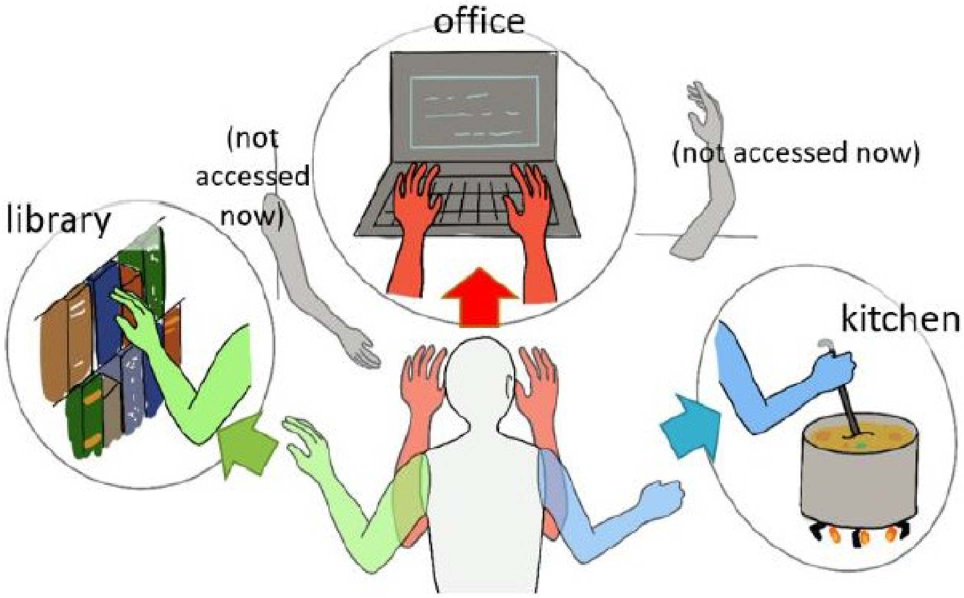


Fig. 50 Daily life scenario of multi-presence task by Ubiquitous Body

be temporarily used by others. It is expected that these systems will develop regardless of the number of tasks, the physical distance, and even the single or multiple user. In this thesis, this kind of ubiquitous SRL application is defined as "Ubiquitous body". Fig. 50 shows an example of a usage scenario of a Ubiquitous body in a daily life environment.

The concept of multi-presence has existed for a while [106], but in recent years, especially with the restriction of movement due to COVID-19, the benefits and demand for multi-presence have rapidly increased, where the body can be in one place but also in several other places [124] [125]. As an example of such multitasking between multiple locations, monitoring and assistance of autonomous robots have attracted much attention. For example, there are robots that are remotely controlled the work in stores such as convenience store chains [126]. This does not solve the shortage of manpower because each robot is operated by a single operator who is immersed in the robot from a remote location. On the other hand, when a robot is used to perform complex tasks such as stocking items, it can automatically carry rice balls and lunch boxes with certain specifications by learning how to grasp them through pre-programming. However, it is difficult for a fully automatic robot to handle cases where it requires to grab an object that it has never experienced before such as a newly released product, or when an error occurs such as dropping an existing product. A human operator will need to temporarily intervene in the robot's work by teaching it how to grab the new object or correcting the error. Thus, it is hoped that a system in which one person can monitor and assist multiple robots and reduce manpower is possible by having multiple robots operate basically on autopilot, but having a human operator involved only when an error occurs or intervention is needed.

As in the case of dual-tasking, the definition of the term multitasking often includes not only the strict situation of performing multiple tasks completely simultaneously, but also switching between several tasks as needed. In the case of using a SRL system to reproduce six multitasks, if we aim for perfect simultaneity as in the former case, we need to develop a operation system and FB system to operate each of the six robot arms in six locations (e.g., the first arm can be operated by the right foot like a joystick, the second arm by the left foot, the third arm by the tilt of the head, etc.). In addition, it is necessary to develop an environment presentation system that can monitor all the work areas simultaneously (e.g., superimposing six semi-transparent images, or dividing the screen into six sections to present the respective information, etc.). On the other hand, the latter case of multitasking, in which task switching is a prerequisite, can be further divided into two possibilities. One is a type based on dual-tasking. As in previous systems for dual-presence tasks, the task performed by the natural body is used as the main task, and one subtask is selected from among the other five tasks, and the subtasks are switched as necessary. The other type is based on teleoperation. One of the six tasks is used as the main task at a time, and it is switched in sequence. In the former, the basis is dual-tasking, so the current operation system and FB systems for dual-presence tasks can be applied. However, as for the environment presentation system, the configuration of it needs to be changed because it is necessary to be able to view all the environments when selecting which task should be the next subtask. In the latter case, the basis of the system is a single task, and we are not bound by the design theory for dual-tasking discussing in this thesis, and can adopt the conventional method of teleoperation research. However, an environment presentation system is also required in this case to obtain information on the other environment by some means when selecting which task to move to next.

Thus, the new cognitive challenge that must be considered in the case of a multi-presence task in addition to a dual-presence task system, is the process of selecting the next task to which attention should be moved, and the design of the attention required for it. With regard to this shifting of attention during task switching, there are two possible ways of doing this: passive and active. In passive switching, users notice that a fire has broken out in a certain room by seeing the image of room or hearing the alarm, and switch our attention to it. In active switching, users remember that they twisted the dial of a toaster in a certain room about five minutes ago, and look for that room to check if it is burnt. The simultaneous monitoring of multiple autonomous robots being explored in the convenience store chain mentioned above is close to the former context. In this case, the task to be focused on next is presented by the system, thus the process of task searching is omitted. On the other hand, as mentioned at the beginning of this thesis, there is a limit to the number of errors that can be assumed in advance, so it is difficult to completely eliminate the process of task searching in order for human to intervene. In such an active task searching process, it is known that, for example, in a visual search task, the larger the number of target stimuli to be explored, the longer the search time (set size effect) [127] [128]. If we think about this in terms of multi-presence task, the more tasks there are, the more difficult it is to visually find the image of the target task. In addition, the larger the number of tasks, the more difficult it is to keep them in memory due to the limitations of working memory [129] [130], and the more difficult it is to manage which task to pay attention to and when. For example, you put bread in the toaster, put the pot on the fire, answer the visitor's chime, notice it's raining, rush to put the laundry in, the phone rings, and by the time you've finished talking, you've forgotten about the bread you put in the toaster in the first place.

The problem is that the task searching is scanning type. That is, for example, when checking the image of 10 environments from the first one, it takes as much time as the number of all tasks to reach the image of the desired environment. As a result, the performance of multitasking is degraded. If the user remembers where the information of the task they wants to focus on next is indicated, the time required for the task searching will decrease. However, when the number of tasks increases, it is difficult to keep all of them in memory. In an environment presentation system for multitasking, it is necessary to have a mechanism that allows easy search, switching, and execution of a specific task while providing a comprehensive view of all environments. In this thesis, we apply the environment presentation system for dual-presence to propose a multi-environment presentation system that presents multiple tasks in the same arrangement as the actual location of environments, and try to achieve both a comprehensive view of the environment and ease of exploration and execution.

6.2 Prototype development

In the multi-presence task, the users mainly focus on one or two tasks while simultaneously paying "continuous partial attention" [131] to other tasks and switching their focus depending on task state. To gain the task state awareness, environment information, such as images or audio, and body state information including haptic sensation or proprioception are available. In this paper, we focused on developing the visual information presentation interface as a first step. The important requirements for the vision presenting system are follows.

1. Users can see all environments even when they are focusing on one environment.
2. Users can find the environment they want to see immediately.

In this thesis, we have already proposed a dual-image presenting system that superimposes two half-transparent image layers for concurrent tasks at two distant places [132]. Ubiquitous body system can be considered to the expands and more complex system of this idea. Especially when the number of environments increases, it is difficult to perform physical manipulation because the size of each image is getting smaller, or it becomes difficult to distinguish each image because the layer number is increased. In addition, the ease of finding information from many images (second requirement) are not clarified in these systems.

Therefore, we designed a new vision presenting interface for the ubiquitous body system as shown in Fig. 51. There are two half-transparent layers, one is for the overall view and the other is for the detailed view. The transparency ratio can be changed by the user's upper body posture as shown in Fig. 51. In the overall view, users can choose the environment with their face direction and it is shown in the detailed view. With this design, the users can see an image of good enough size for manipulation while maintaining the ability to see other environments. In addition, each environment's images on the overall view are arranged in the same place as the real-world placement. The system was designed with reference to studies on visual surveillance systems showing the camera image with the floor map for effective monitoring [133] [134]. This design is expected to be effective to the vision interface of the ubiquitous body which also requires to manage many tasks at once and move user's attention efficiently.

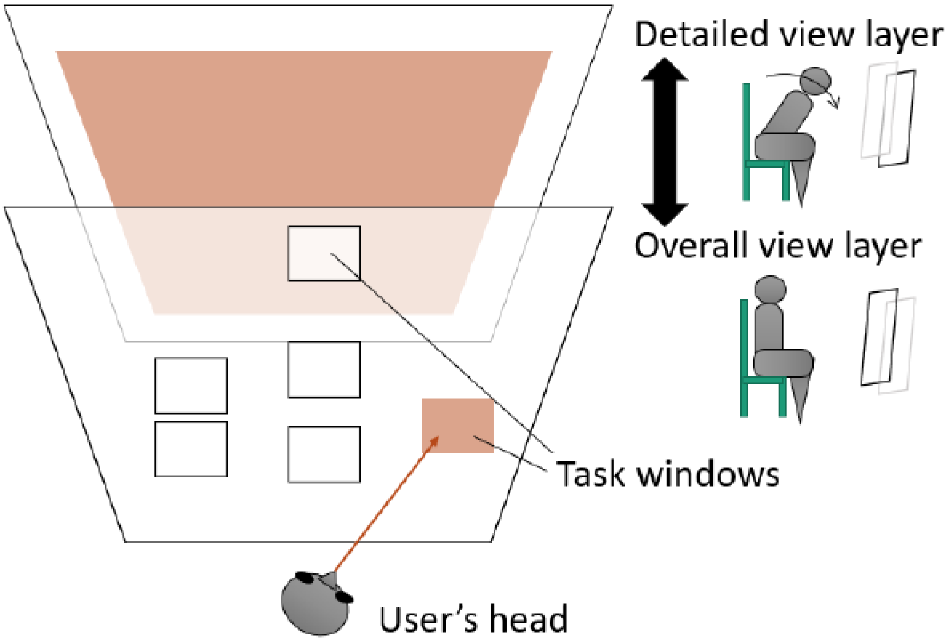


Fig. 51 Mechanism of Multi-presence task system

As for the variables of this system prototype, e.g. setting of the transparency ratio, each window size, or setting of the upper body angle which is used for switching view, it should be verified individually. In this report, we focus on the effect of spatial arrangement of the information because it is considered to affect the reaction time or memory in aspect of cognitive science [135]. These window arrangement on the real map is also used in the user interfaces of computer games [136], but few studies discussed how it affects the management of manipulation tasks in real world especially in case of dealing with many tasks. In the next section, we conducted the case study to investigate the effect of spatial arrangement of the task windows and the usability of this interface prototype.

6.3 Evaluation

6.3.1 Overview

The purpose of the case study is to clarify the effect of spatial arrangement of the task windows and the usability of the interface, along with to investigate the user's behavior when they try to perform too many tasks simultaneously. We set three conditions regarding the arrangement of the task window on overall view as shown in Fig. 52.

- Map: fix window's position with the map to create the spatial relationship of vision information same as the real-world placement.
- Array: fix window's position with an array to create the spatial relationship of vision information not same as the real-world placement. (participants can still

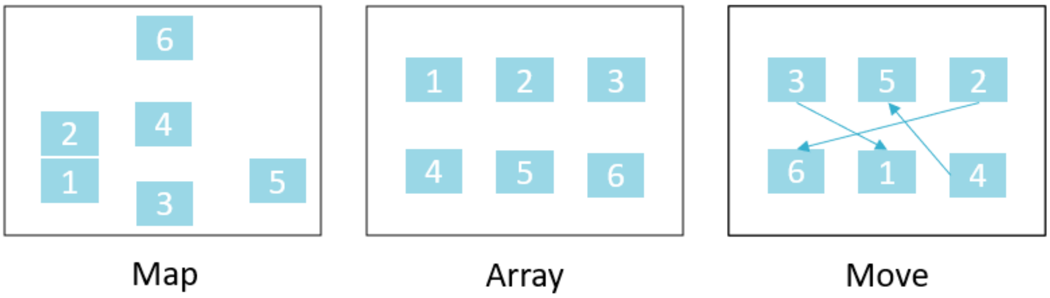


Fig. 52 Condition of image presenting

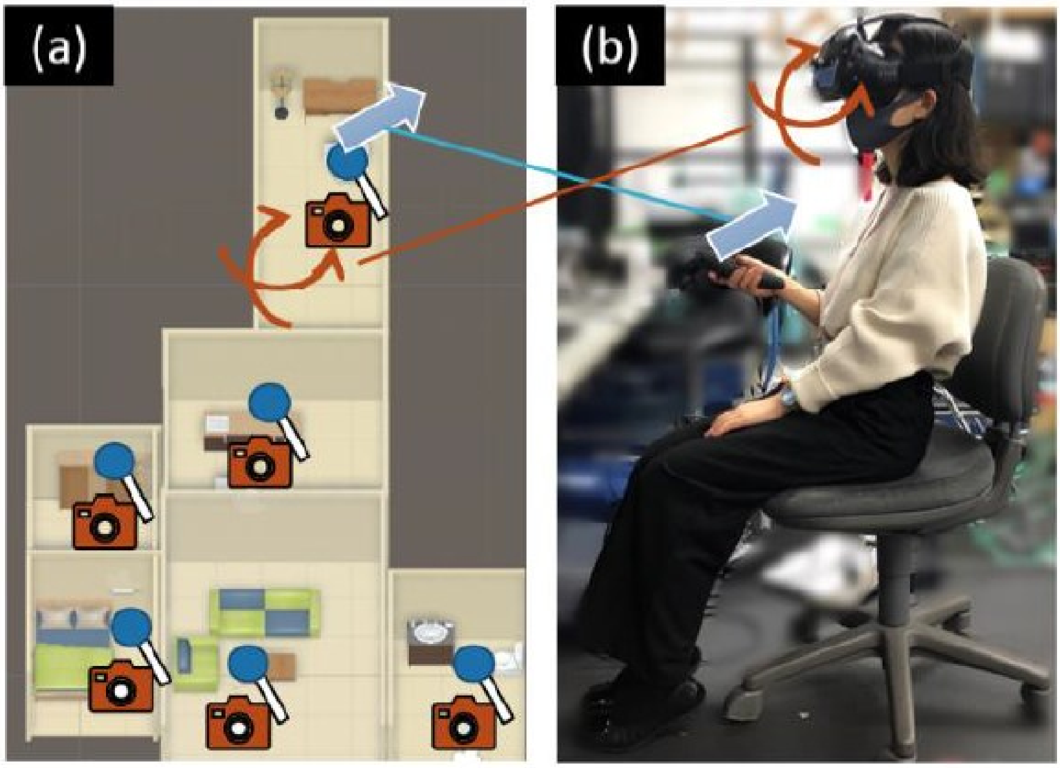


Fig. 53 Overview of task settings

reconstruct new spatial relationship of vision information in this condition)

- Move: change window's position each time to vanish the spatial relationship of vision information.

The study environment is constructed in virtual reality using Unity software [80]. Participants accessed the environment by using an immersive head mount display VIVE [112]. As shown in Fig. 53(a), 6 rooms are in the scene and there are 6 ubiquitous bodies. Each ubiquitous body consists of a robot arm and camera, and the movement of the ubiquitous bodies of each room are synchronized to participants' movement only when participants choose the room and proceed to the detailed layer. 4 participants took part in this case study, all of them are healthy adult students in their twenties (mean age=24, SD=0.71, male=3), and none of them directly involved in this project.

6.3.2 View Settings

Fig. 54 shows the participant view and its structure. As mentioned previously,

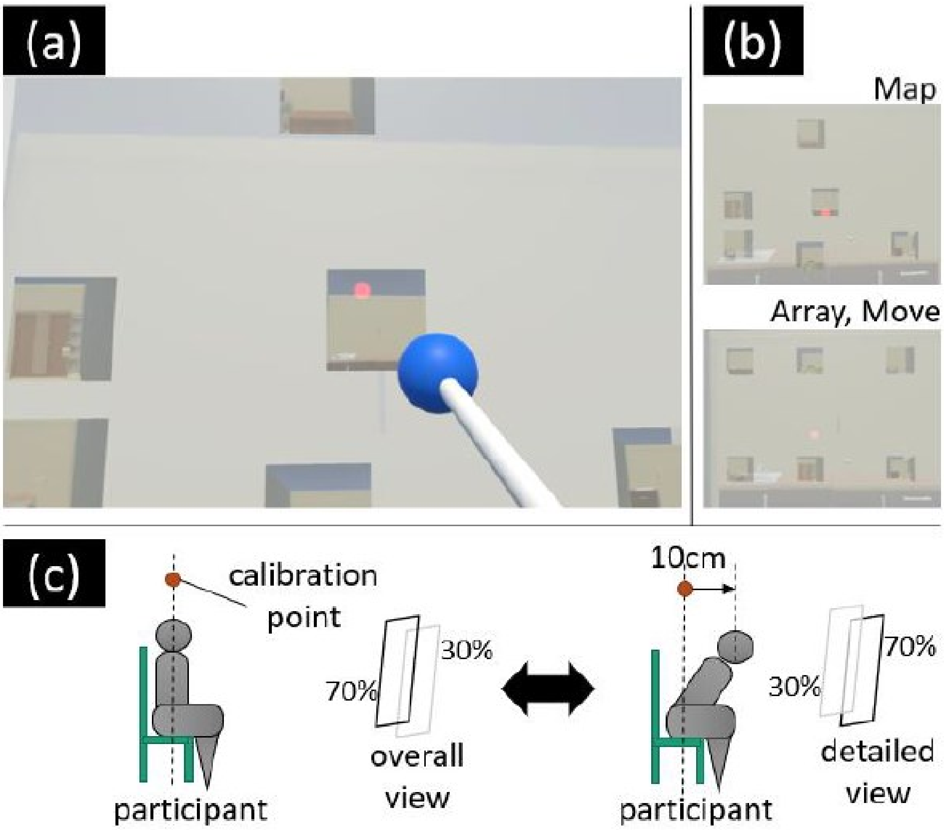


Fig. 54 Subject's view of the multi-presence system and its operation

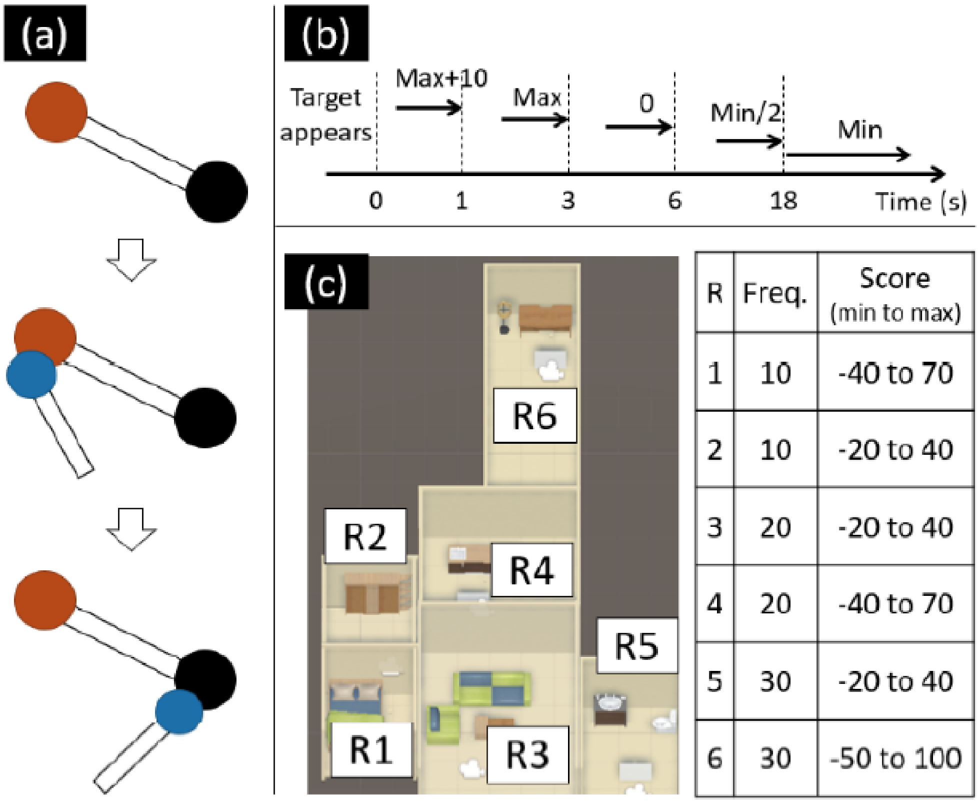
there are three arrangements of the task window which is on the overall view layer (Fig. 54(b)). In any arrangements, all windows are in the participant's vision field when they face forward. Before starting the experiment, the calibration point to switch the layers is set for each participant as shown in Fig. 54(c). The transparency ratio of two layers was 70% : 30%, and it can be switched by participant's movement. A simple direction messages (e.g. "start", "finish") and current score are also shown in the participant view.

6.3.3 Task Settings

The tasks are almost the same in each room and it was set assumed trajectory manipulation using a robot arm in the future. As shown in Fig. 55, the target object appears at a certain timing in the room. Participants should touch the start point (red sphere) and then stop point (black sphere) using their ubiquitous arm as soon as possible after the target object appears. The score is decided depending on the reaction time from the target object appearing until participants touch the start point. The faster reaction gets more point, and the slower reaction lose more point. The criteria of reaction time were decided from the result of advance player test. The tasks in each room are featured by “frequency” of the target object appearing and “score range” when they get a score (Fig. 55(c)). For example, the task of room2 is high frequency but users can get a small score even if they could react faster. These task features are informed to the participants before the practice.

6.3.4 Procedure

Before starting a trial, participants are given enough time to practice on the tasks with each condition. Participants are instructed to get as higher score as possible, and maintain a high performance in all tasks. The trial starts at the experimenter’s



R	Freq.	Score (min to max)
1	10	-40 to 70
2	10	-20 to 40
3	20	-20 to 40
4	20	-40 to 70
5	30	-20 to 40
6	30	-50 to 100

Fig. 55 Task setting in each room and its characteristics

Table IV Statements of the questionnaire

No.	Category	Statement
Q1	Task recognition	Detect tasks by its visual background.
Q2		Detect tasks by its location.
Q3	Attention movement	I tried to find the task what I want to do next.
Q4		I did the task which recently appears.

cue (also shown in participant view as the text message) and ends automatically after 2 minutes. Participants attempt to perform six tasks simultaneously, once for each of the three conditions. The order of conditions is randomized in every subject. At the end of each condition, a questionnaire with a seven-point Likert scale is administered as a subjective evaluation (see questions in Table IV). After all the trials are completed, an interview about the usability of the interface is conducted.

6.4 Result and discussion

6.4.1 Result

Fig. 57 and Fig. 56 show the participant mean values of task score and reaction time in each condition, the number of sets completed during one trial, and the results of subjective evaluation. Unfortunately, we still have only a small number of participants, so this short paper mainly focused on the tendency of the data and behavioral considerations from the interview results, and we will leave the statistical processing and further discussion to a subsequent report. As for the task performance, the total score was the highest in the map condition, more than twice as high as the score for the array condition and the move condition as shown in Fig. 57(a).

As for the reaction time from the appearance of the target object to the time when participants touched it, there seemed to be not much difference between the move condition and the array condition, but the Map condition was about one second faster than those two conditions. As for the subjective evaluation (see Fig. 56), the score for task recognition from environmental information (Q1) was not very high for any of

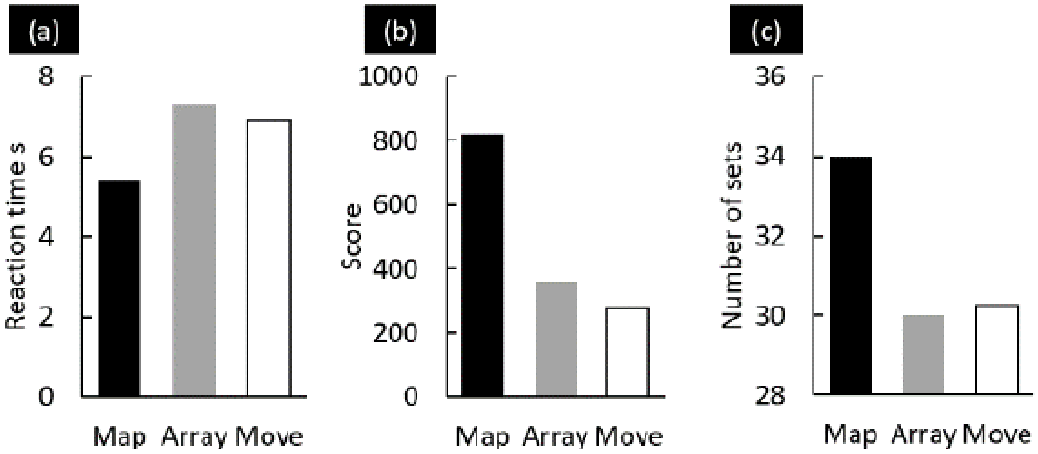


Fig. 57 Results of the case study

(a)average reaction time from appearing the target object to participants touching it, (b)average final score, (c)average number of completed sets.

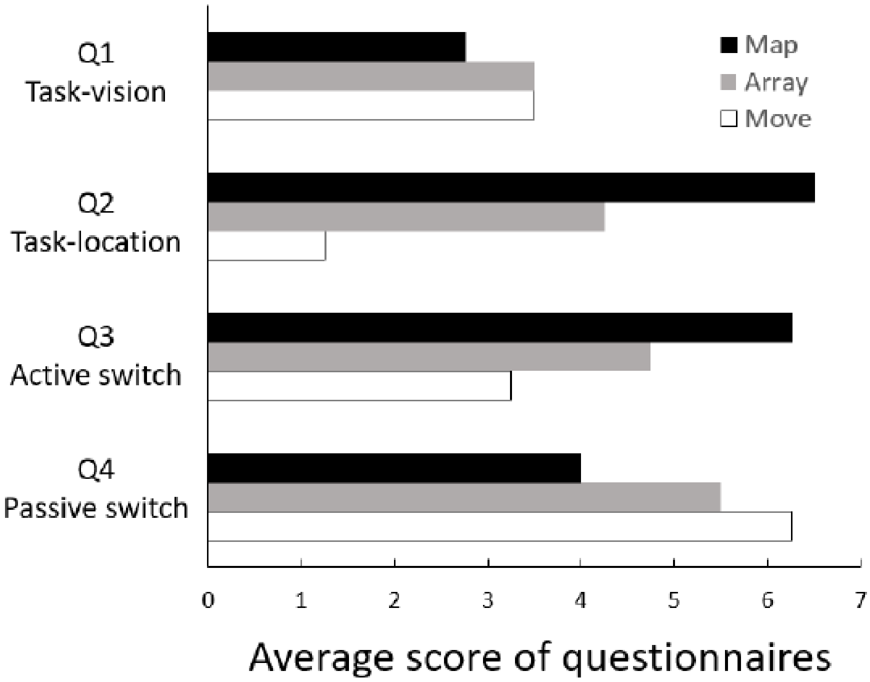


Fig. 56 Average scores of questionnaires

the indices, while the score for task recognition from location information (Q2) was the highest in the Map condition. As for the attention movement strategies (Q3: act with strategy or Q4: react what is appeared), there seemed to be an opposite trend between the map condition and the move conditions.

6.4.2 Discussion

Before the start of the case study, we assumed that the task score will be highest in the map condition because participants can make the strategy by associating spatial task positions and each task features. We also assumed that this possibility of making strategy in the map condition leads to a smaller number of task sets and larger average reaction time because some tasks (especially lower point tasks) would be ignored under the strategy to get a higher score. However, as shown in Fig. 55, the presentation of realistic spatial arrangement tended to show good results not only in the final scores but also in the number of task sets and reaction time. In the interview, two participants said that it was easy to pay attention to check the next task on the over view layer even while doing the current task on the detailed view layer. This may lead to optimizing attention switching to each task by having a spatial map image of them by the user when performing multiple tasks simultaneously. This is a very interesting suggestion that may lead to the importance of allowing users to perceive the ubiquitous body as a single body. Through this case study with small number of participants, the limitations and improvements to the study design were revealed before increasing the number of participants. First, the task was periodic and easy to actively manage. In contrast, we wondered if the spatial arrangement of information would not be very effective for tasks that involve passive attention shifting to deal with irregular problems such as responding to phone ringing. Second, when assumed the real use case of the ubiquitous body, the positional relationship of body parts may change dynamically. In this situation, presenting a spatial relationship of each task may be more effective in managing many tasks. On the other hand, some disadvantages could be caused by presenting a spatial relationship precisely (e.g. when one body part is at very far from others), so it also need to verify how accurately we should represent the positional relationships. In the future work, we will update the experimental system considering these limitations and investigate the effect of having the spatial relationship of each bodies on efficient managing of the ubiquitous body.

Chapter 7: Conclusion

7.1 Summary

The purpose of this study is to achieve dual-presence tasks using human augmentation technology. We set the research question of how to design a system that can perform dual-presence tasks efficiently, and discussed the design theory of SRL to improve the performance of dual-presence tasks. The contribution of this paper is to propose the concept of a Detachable body as a new application of the human augmentation, and to propose three design theories based on human cognitive characteristics in dual tasks. First, through the development of an intermittent operation system using face vector pointing, it was shown that there is a trade-off between reducing instruction error and reducing attentional load, and that the hardware should be designed to satisfy the function even with "rough instructions" with low attentional load. Second, through the development of a state FB system for the SRL using vibration array, it was shown that the introduction of partial automatic control may increase the sense of distrust and anxiety toward the SRL and interfere with the appropriate distribution of attention, and inducing FB system of SRL states if effective to reduce them. Third, through the development of a dual-presence system using the disparity effect, it was shown that a strong sense of simultaneous presence and equal input of information from each environment makes it difficult to switch attention, and the system should be designed so that the focus of attention can be clarified while simultaneously presenting information from each environment.

This thesis argues for the importance of selecting design elements that satisfy the required functions when designing the SRL, considering how they deprive humans of attention and how they inhibit or facilitate the switching and distribution of attention, and experimentally substantiates some of this with the three specific examples above. Furthermore, based on these three contributions, we discussed the effect of the presence or absence of embodiment in the SRL on the user's attention allotment during a dual-presence task. This presents a concrete question of "what are the benefits of using a "body" instead of just a robotic arm for task support" that has been difficult to discuss in the field of human augmentation.

7.2 Future work

As mentioned in Chapters 5 and 6, it is necessary to continue investigating the effects of the presence or absence of embodiment on the robot arm on dual-presence tasks, and the application to the design theory of the SRL to perform multi-presence tasks. On the other hand, there are several topics that need to be considered in completing the overall system of Detachable body and putting it out into the society.

First, regarding the impact of embodiment on tasks, it is necessary to conduct the verification of the impact of detachability on the attention allotment and the user experience. For example, if the embodiment of the robot arm produces positive effects such as reduced required attention and increased reliability to the robot, it is also the benefit for inducing embodiment to the detached body. In that case, when performing a task with a robot at a remote location, the performance and usability of a robot that has been worn at least once will be better than that of a robot that has never been worn. Also, the fact that the detached arm retains the embodiment of a particular person may have a new impact on the user experience as they interact with the people around them. For example, when someone collaborates with an ordinary robotic arm installed in the environment, the person may think of the robot as just a machine and treat it roughly, but if he or she recognizes that it is a part of someone's body, he or she may treat it more gently, or may be able to work more effectively because he or she knows the person's habits.

Next, regarding the hardware development of the Detachable body system, elements other than interface systems should also be designed considering their impact on the user's attention allocation during the dual-presence task. For example, when the Detachable body is worn on the shoulder, depending on the placement of the degrees-of-freedom of the robot arm, the work area of the natural body and the movable area of the robot arm may overlap significantly, making it difficult to perform each task. It may be issue that interrupt the optimal attention allocation in the task. We have been addressing this from the viewpoint of setting the work area in the case of a wearable robot arm [137] [138]. However, in the case of a robot arm whose positional relationship with the natural body is not fixed, such as a detachable body, it is necessary to consider the interference with the natural body or environment, such as fixing the movement angle of some joints depending on the situation.

Finally, it is necessary to take into account the negative aspects of the social advancement of such technologies that may fundamentally change human lifestyles. For example, the Detachable body and other SRL applications introduced in this paper are intended to assist concurrent tasks and shorten the working time. However, since there is no limit to human greed, we cannot deny the possibility that if one person is able to do many things at the same time, the amount of work assigned to one person will increase, and as a result, the person will become even busier. In addition, as shown in the discussion in Chapter 5, it has been suggested that long-term use of the extended body actually causes changes in brain activity. Whether such changes are plastic or irreversible is a major ethical question. If our cognition and the way we use our bodies are fundamentally altered by the continued use of the system, no one can foresee the adverse effects, such as the physical and mental health implications that would follow. Thus, when we introduce augmented body technology into society, we must not forget to consider its social structural impact and biological impact on human beings.

References

[1] 株式会社野村総合研究所, "平成２９年度商取引適正化・製品安全に係る事業（家事支援サービス業を取り巻く諸課題に係る調査研究）調査報告書," 3 2018. [Online]. Available: https://www.meti.go.jp/meti_lib/report/H29FY/000261.pdf. [Accessed 12 2021].

[2] "iRobot ルンバ," iRobot, 2021. [Online]. Available: https://www.irobot-jp.com/roomba/. [Accessed 31 12 2021].

[3] "laundroid," Biccamera (seven dreamers laboratories), 2021. [Online]. Available: https://www.biccamera.com/bc/c/topics/laundroid/index.jsp. [Accessed 31 12 2021].

[4] R. Raisamo, I. Rakkolainen, P. Majaranta, K. Salminen, J. Rantala and A. Farooq, "Human augmentation: Past, present and future," *International Journal of Human-Computer Studies,* vol. 131, 2019.

[5] B. Alicea, "An Integrative Introduction to Human Augmentation Science," in *ArXiv*, 2018.

[6] H. Kazerooni, "A Review of the Exoskeleton and Human Augmentation Technology," in *ASME 2008 Dynamic Systems and Control Conference*, 2008.

[7] M. Daily, A. Oulasvirta and J. Rekimoto, "Technology for Human Augmentation," *Computer,* vol. 50, no. 2, pp. 12-15, 2017.

[8] J. Mcgrenere and W. Ho, "Affordances: Clarifying and Evolving a Concept," in *Conference: Proceedings of the Graphics Interface 2000 Conference*, Montréal, 2000.

[9] C. Kim, M. Jung, S. Kim and K. Kim, "Controlling the Sense of Embodiment for Virtual Avatar Applications: Methods and Empirical Study," *JMIR Serious Games,* vol. 8, no. 3, p. e21879, 2020.

[10] R. Fribourg, F. Argelaguet, A. Lecuyer and L. Hoyet, "Avatar and Sense of Embodiment: Studying the Relative Preference Between Appearance, Control and Point of View," *IEEE Trans Vis Comput Graph,* vol. 26, no. 5, pp. 2062-2072, 2020.

[11] M. Raab and D. Araújo, "Embodied Cognition With and Without Mental Representations: The Case of Embodied Choices in Sports," *Front. Psychol.,* vol. 10, no. 1825, 2019.

[12] L. Shapiro and S. A. Stolz, "Embodied cognition and its significance for education," *Theory and Research in Education,* vol. 17, no. 1, pp. 19-39, 2019.

[13] T. Ziemke, "What's that Thing Called Embodiment?," in *Proceedings of the Annual*

Meeting of the Cognitive Science Society, 2003.

[14] K. Kilteni, R. Groten and M. Slater, "The Sense of Embodiment in Virtual Reality," *Presence: Teleoperators and Virtual Environments,* vol. 21, no. 4, pp. 373-387, 2012.

[15] K. Kilteni, R. Groten and M. Slater, "The sense of embodiment in virtual reality," *Presence: Teleoperators and Virtual Environments,* vol. 21, no. 4, pp. 373-387, 2012.

[16] A. Rawal, C. J. Harmer, R. J. Park, U. D. O'Sullivan and J. M. G. Williams, "A Sense of Embodiment Is Reflected in People's Signature Size," *PLoS ONE,* vol. 9, no. 2, p. e88438, 2014.

[17] Llorens-Bonilla and H. Asada, "A Robot on the Shoulder : Coordinated Human - Wearable Robot Control using Coloured Petri Nets and Partial Least Squares Predictions," in *IEEE Int. Conf. Robot. Autom.*, 2014.

[18] F. Parietti and H. Asada, "Independent, voluntary control of extra robotic limbs," in *Proc. -IEEE Int. Conf. Robot. Autom.*, 2017.

[19] T. Sasaki, M. Y. Saraiji, C. L. Fernando, K. Minamizawa and M. Inami, "MetaLimbs: multiple arms interaction metamorphism," in *ACM SIGGRAPH 2017 Emerg. Technol. -SIGGRAPH '17*, 2017.

[20] 岩崎悠希子, 中林幸輝, 高橋翔太, 飯塚修平, 天野浩平, 安藤孝三 and 岩田浩康, "直感的な随意操作が可能な【第三の腕】に関する研究ー第八報 : “Detachable Body”のコンセプトデザインー," in *第36回日本ロボット学会学術講演会*, 2018.

[21] M. Slater, D. Pérez Marcos, H. Ehrsson and M. Sanchez-Vives, "Inducing illusory ownership of a virtual body," *Frontiers in Neuroscience,* vol. 3, no. 2, pp. 214-220, 2009.

[22] C. Lopez, C. Bieri, N. Preuss and F. Mast, "Tactile and vestibular mechanisms underlying ownership for body parts: A non-visual variant of the rubber hand illusion," *Neuroscience Letters,* vol. 511, no. 2, pp. 120-124, 2012.

[23] Y. Tong and J. Liu, "Review of Research and Development of Supernumerary Robotic Limbs," *Journal of Automatica Sinica,* vol. 8, no. 5, pp. 929-952, 2021.

[24] D. Kahneman, "Attention and Effort," *Psychology,* 1973.

[25] A. T. Welford, "THE 'PSYCHOLOGICAL REFRACTORY PERIOD' AND THE TIMING OF HIGH-SPEED PERFORMANCE—A REVIEW AND A THEORY," *British Journal of Psychology,* vol. 43, no. 1, pp. 2-19, 1952.

[26] R. Beurskens and O. Bock, "Age-Related Deficits of Dual-Task Walking: A Review," *Neural Plast,* vol. 2012, no. 131608, 2012.

[27] C. Chipunza and A. Mandeya, "Dual-Task Processing: Effects of Task Difficulty and

Stimulus Similarity on Dual-Task Performance," *South African Journal of Psychology,* vol. 35, no. 4, pp. 684-702, 2005.

[28] D. M. Venema, E. Bartels and K. C. Siu, "Tasks matter: a cross-sectional study of the relationship of cognition and dual-task performance in older adults," *Journal of geriatric physical therapy,* vol. 36, no. 3, pp. 115-122, 2013.

[29] S. Opiyo, J. Zhou, E. Mwangi, W. Kai and I. Sunusi, "A Review on Teleoperation of Mobile Ground Robots: Architecture and Situation Awareness," *International Journal of Control Automation and Systems,* vol. 19, pp. 1384-1407, 2021.

[30] L. Jing, H. Wei and Y. Chenguang, "Combined perception, control, and learning for teleoperation: key technologies, applications, and challenges," *Cognitive Computation and Systems,* vol. 2, no. 2, pp. 33-43, 2020.

[31] M. R. Sarder, F. Ahmed and B. A. Shakhar, "Design and implementation of a lightweight telepresence robot for medical assistance," in *2017 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, Cox's Bazar, 2017.

[32] O.-H. Kwon, S.-Y. Koo, Y.-G. Kim and D.-S. Kwon, "Telepresence robot system for English tutoring," in *2010 IEEE Workshop on Advanced Robotics and its Social Impacts*, Seoul, 2010.

[33] N. Harikrishnan, S. Ann Soni, A. Mary Alex, V. Menon and V. C Nair, "Virtual Interactive Reality Telepresence Robot," in *Proceedings of the International Conference on Systems*, 2021.

[34] G. I. o. Technology, "Enhancing Stroke Generation and Expressivity in Robotic Drummers - a Generative Physics Model Approach," Georgia Institute of Technology, [Online]. Available: https://phys.org/news/2016-02-wearable-robot-musicians-three-armed-drummers.html. [Accessed 31 1 2022].

[35] J. Lobo-Prat, P. Kooren and A. Stienen, "Non-invasive control interfaces for intention detection in active movement-assistive devices," *Journal of NeuroEngineering and Rehabilitation,* vol. 11, no. 1, p. 168, 2014.

[36] P. Bustillo-Casero, I. Villarrasa-Sapiña and X. García-Massó, "Effects of dual task difficulty in motor and cognitive performance: Differences between adults and adolescents," in *Hum. Mov. Sci.*, 2017.

[37] J. S. D. Watson, "Supertaskers: Profiles in extraordinary multitasking ability," *Psychonomic Bulletin & Review,* vol. 17, pp. 479-485, 2010.

[38] S. David and M. Jason, "Supertaskers and the Multitasking Brain," *Scientific*

American Mind, vol. 23, no. 1, pp. 22-29, 2012.

[39] B. Neilson, C. Craig, A. Travis and M. Klein, "A review of the limitations of Attention Restoration Theory and the importance of its future research for the improvement of well-being in urban living," *Visions of Sustainability,* pp. 59-67, 2019.

[40] D. D. Salvucci and N. A. Taatgen, "Threaded cognition: An integrated theory of concurrent multitasking," *Psychological Review,* vol. 115, no. 1, pp. 101-130, 2008.

[41] C. Wickens, "Processing Resources in Attention, Dual Task Performance, and Workload Assessment," *Computer Science,* 1981.

[42] K. J. o. c. 2. 3. Oberauer, "Working Memory and Attention – A Conceptual Analysis and Review," *Journal of cognition,* vol. 2, no. 1, p. 36, 2019.

[43] C. Dimov, "Uncovering cognitive constraints is the bottleneck in resource-rational analysis," *Behavioral and Brain Sciences,* vol. 43, p. E8, 2020.

[44] F. Paas and J. Van Merriënboer, "Cognitive-Load Theory: Methods to Manage Working Memory Load in the Learning of Complex Tasks," *Current Directions in Psychological Science,* vol. 29, no. 4, pp. 394-398., 2020.

[45] D. Kahneman, Attention and Effort, New Jersey: PrenticeHall Inc., 1973.

[46] C. D. Wickens, "Multiple resources and performance prediction," *Theoretical Issues in Ergonomics,* vol. 3, no. 2, pp. 159-177, 2002.

[47] C. Spence, "Multisensory attention and tactile information-processing," *Behavioural Brain Research,* vol. 135, no. 1-2, pp. 57-64, 2002.

[48] L. Lin, "Multiple Dimensions of Multitasking Phenomenon," *International Journal of Technology and Human Interaction,* vol. 9, no. 1, pp. 37-49, 2015.

[49] J. Rubinstein, D. Meyer and J. Evans, "Executive control of cognitive processes in task switching," *Journal of experimental psychology,* vol. 27, no. 4, pp. 763-97, 2001.

[50] D. Wickens, R. S, Gutzwiller and A. Santamaria, "Discrete task switching in overload: A meta-analyses and a model," *International Journal of Human-Computer Studies,* vol. 79, pp. 79-84, 2015.

[51] G. Lin and S. Carlile, "Costs of switching auditory spatial attention in following conversational turn-taking," *Frontiers in neuroscience,* vol. 9, no. 124, 2015.

[52] W. Glenn and A. Alan, "Task switching and the measurement of “switch costs”," *Psychological Research,* vol. 63, no. 3, pp. 212-233, 2000.

[53] T. Strobach, R. Liepelt, T. Schubert and A. Kiesel, "Task switching: effects of practice on switch and mixing costs," *Psychological Research,* vol. 76, pp. 74-83, 2012.

[54] J. Han, G. Waddington, R. Adams, J. Anson and Y. Liu, "Assessing proprioception: A critical review of methods," *Journal of sport and health science,* vol. 5, no. 1, pp. 80-90, 2016.

[55] S. Gaur and B. Krishnamoorthy, "Emergence of multipresence - A theoretical underpinning," *International Journal of Business Information Systems,* vol. 27, no. 1123, 2018.

[56] E. Goffman, in *The Presentation of Self in EverydayLife*, New York, The Overlook Press, 1959, pp. 17-25.

[57] C. Oh, J. Bailenson and G. Welch, "A Systematic Review of Social Presence: Definition, Antecedents, and Implications," *Front. Robot. AI ,* vol. 5, no. 114, pp. 1-35, 2018.

[58] A. Steed and R. Schroeder, in *Collaboration in Immersive and Non-immersive Virtual Environments*, Switzerland, Springer International Publishing, 2015, pp. 263-282.

[59] S. Yamen, S. Shota, F. Charith Lasantha, M. Kouta and T. Susumu, "Layered telepresence: simultaneous multi presence experience using eye gaze based perceptual awareness blending," in *ACM SIGGRAPH 2016 Emerging Technologies (SIGGRAPH '16)*, 2016.

[60] I. Farkhatdinov and J.-H. Ryu, "Teleoperation of multi-robot and multi-property systems," in *2008 6th IEEE International Conference on Industrial Informatics*, 2008.

[61] T. Susumu, "Telexistence," *Journal of the Robotics Society of Japan,* vol. 33, no. 4, pp. 215-221, 2015.

[62] H. Martins and R. Ventura, "Immersive 3-D teleoperation of a search and rescue robot using a head-mounted display," in *2009 IEEE Conference on Emerging Technologies & Factory Automation*, Palma de Mallorca, 2009.

[63] B. Laha, J. N. Bailenson, A. S. Won and J. O. Bailey, "Evaluating Control Schemes for the Third Arm of an Avatar," *Presence: Teleoperators and Virtual Environments 2016,* vol. 25, no. 2, p. 129–147, 2016.

[64] Llorens-Bonilla, F. Parietti and H. Asada, "Demonstration-based control of supernumerary robotic limbs," in *IEEE Int. Conf. Intell. Robot. Syst.*, 2012.

[65] B. Llorens-Bonilla and H. Asada, "Control and Coordination of Supernumerary Robotic Limbs Based on Human Motion Detection and Task Petri Net Model," in *Proceedings of the ASME 2013 Dynamic Systems and Control Conference.*, California, 2013.

[66] F. Y. Wu and H. H. Asada, ""Hold-and-manipulate” with a single hand being assisted

by wearable extra fingers," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015.

[67] T. Sheridan and R. Parasuraman, "Human-Automation Interaction," *Reviews of Human Factors and Ergonomics,* vol. 1, no. 1, pp. 89-129, 2005.

[68] R. Parasuraman, T. B. Sheridan and C. D. Wickens, "A model for types and levels of human interaction with automation," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans,* vol. 30, no. 3, pp. 286-297, 2000.

[69] E. Oyama, W. K. Yoon, Y. Wakita, H. Tanaka, M. Yoshikawa, T. Sakaguchi and Y. Matsumoto, "Development of evaluation indexes for assistive robots based on ICF," in *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*, 2012.

[70] D. a. H. (. International Classification of Functioning, "WHOFIC Maintenance Platform," International Classification of Functioning, Disability and Health (ICF), [Online]. Available: https://icd.who.int/dev11/l-icf/en. [Accessed 31 1 2022].

[71] E. Oyama, W. Yoon, Y. Wakita, H. Tanaka, M. Yoshikawa, T. Sakaguchi and Y. Matsumoto, "Development of evaluation indexes for assistive robots based on ICF," in *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*, 2012.

[72] R. C. Simpson and S. P. Levine, "Voice control of a powered wheelchair," *in IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 10, no. 2, pp. 122-125, 2002.

[73] A. Jackowski, M. Gebhard and A. Gräser, "A novel head gesture based interface for hands-free control of a robot," in *2016 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, 2016.

[74] A. Lanata, A. Greco, G. Valenza and E. P. Scilingo, "On the tridimensional estimation of the gaze point by a stereoscopic wearable eye tracker," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2015.

[75] P. M. Tostado, W. W. Abbott and A. A. Faisal, "3D gaze cursor: Continuous calibration and end-point grasp control of robotic actuators," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016.

[76] C. Penaloza and S. Nishio, "BMI control of a third arm for multitasking," *Sci Robot,* vol. 3, no. 20, 2018.

[77] P. Jia, H. H. Hu, T. Lu and K. Yuan, "Head gesture recognition for hands-free control

of an intelligent wheelchair," *Industrial Robot: An International Journal,* vol. 34, no. 1, pp. 60-68, 2007.

[78] DINED, "DINED /Anthropometry in design," DINED, [Online]. Available: https://dined.io.tudelft.nl/en/database/tool. [Accessed 31 1 2022].

[79] S. Banbury and D. Berry, "Office noise and employee concentration: Identifying causes of disruption and potential improvements," vol. 48, no. 1, pp. 25-37, 2005.

[80] U. Technologies, "Unity," Unity Technologies, [Online]. Available: https://unity3d.com/jp/unity. [Accessed 31 1 2022].

[81] M. Quest, "Oculus," Quest, Meta, [Online]. Available: https://www.oculus.com/rift. [Accessed 31 1 2022].

[82] 多田隈建二郎, 林聡輔, 清水杜織, 鉄井光, 髙根英里, 渡辺将広, 昆陽雅司 and 田所諭, "Variable Stifness Gripper Mechanism Based on Tufted Jamming Membrane," in *ロボティクス・メカトロニクス　講演会 2019*, 2019.

[83] J. R. Amend, E. Brown, N. Rodenberg and H. M. J. a. H. Lipson, "A Positive Pressure Universal Gripper Based on the Jamming of Granular Material," *IEEE Transactions on Robotics,* vol. 28, no. 2, pp. 341-350, 2012.

[84] K. Amano, Y. Iwasaki, K. Nakabayashi and H. Iwata, "Development of a Three-Fingered Jamming Gripper for Corresponding to the Position Error and Shape Difference," in *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, Seoul, 2019.

[85] C. Li, G. Cui and H. Lu, "The design of an obstacle avoiding trajectory in unknown environment using potential fields," in *2010 IEEE International Conference on Information and Automation, ICIA 2010*, 2010.

[86] H. A. Attia, S. Ismail and H. Y. Ali, "Vehicle safety distance alarming system," in *2016 5th International Conference on Electronic Devices, Systems and Applications (ICEDSA)*, 2016.

[87] J. Perret and E. V. Poorten, "Touching Virtual Reality: A Review of Haptic Gloves," in *ACTUATOR 2018; 16th International Conference on New Actuators*, 2018.

[88] A. M. Okamura, M. R. Cutkosky and J. T. Dennerlein, "Reality-based models for vibration feedback in virtual environments," *IEEE/ASME Transactions on Mechatronics,* vol. 6, no. 3, pp. 245-252, 2001.

[89] Haptx, "Haptx Glove," 2021 HaptX Inc., [Online]. Available: https://haptx.com/. [Accessed 31 1 2022].

[90] V. Guruswamy, J. Lang and W. Lee, "Modelling of haptic vibration textures with

infinite-impulse-response filters," in *2009 IEEE International Workshop on Haptic Audio visual Environments and Games*, 2009.

[91] T. NISHIO, G. ENRIQUEZ, H. YAP, T. YAMAGUCHI and S. Hashimoto, "Evaluation of Blind Robot Manipulation Using Vibratory Haptic Display and Two-joint Robot Arm," in *The Proceedings of JSME annual Conference on Robotics and Mechatronics (Robomech)*, 2015.

[92] L. Rahal, J. Cha and A. E. Saddik, "Continuous tactile perception for vibrotactile displays," in *2009 IEEE International Workshop on Robotic and Sensors Environments*, Lecco, 2009.

[93] C. Mørch, O. Andersen, A. Quevedo, L. Arendt-Nielsen and R. Coghill, "Exteroceptive aspects of nociception: insights from graphesthesia and two-point discrimination," *Pain,* vol. 151, no. 1, pp. 45-52, 2010.

[94] T. NISHIO, G. ENRIQUEZ, H. YAP, T. YAMAGUCHI and S. Hashimoto, "Evaluation of Blind Robot Manipulation Using Vibratory Haptic," in *The Proceedings of JSME annual Conference on Robotics and Mechatronics (Robomec)*, 2015.

[95] K. Nakabayashi, Y. Iwasaki and S. I. H. Takahashi, "Experimental Evaluation of Cooperativeness and Collision Safety of a Wearable Robot Arm," in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2018.

[96] F. Okura, I. Mitsugami, M. Niwa, K. Aoki, C. Zhou and Y. Yagi, "Automatic Collection of Dual-task Human Behavior for Analysis of Cognitive Function," *ITE Transactions on Media Technology and Applications,* vol. 6, no. 2, pp. 138-150, 2018.

[97] K. G. R. S. M. Kilteni, "The Sense of Embodiment in Virtual Reality," *Presence,* vol. 21, no. 4, pp. 373-387, 2012.

[98] R. Newport, Pearce, R and C. Preston, "Fake hands in action: embodiment and control of supernumerary limbs," *Exp Brain Res,* vol. 204, no. 3, pp. 385-395, 2010.

[99] C. Lopez, P. Halje and O. Blanke, "Body ownership and embodiment: Vestibular and multisensory mechanisms," *Neurophysiologie Clinique/Clinical Neurophysiology,* vol. 38, no. 3, pp. 149-161, 2008.

[100] A. Shahar, T. Gregor, M. Christine, M. M. Christoph and B. Olaf, "Neural Basis of Embodiment: Distinct Contributions of Temporoparietal Junction and Extrastriate Body Area," *Journal of Neuroscience,* vol. 26, no. 31, pp. 8074-8081, 2006.

[101] Frédérique de Vignemont, "Embodiment, ownership and disownership," *Consciousness and Cognition,* vol. 20, no. 1, pp. 82-93, 2011.

[102] D. Farizon, P. Dominey and J. Ventre-Dominey, "Insights on embodiment induced by visuo-tactile stimulation during robotic telepresence," *Scientific Reports,* vol. 11, no. 1, 2021.

[103] M. Botvinick and J. Cohen, "Rubber hands 'feel' touch that eyes see," *Nature,* vol. 391, no. 6669, p. 756, 1998.

[104] Y. Iwasaki, K. Ando and H. Iwata, "Haptic Feedback System of the Additional Hand Position for Multiple Task Situations using a Wearable Robot Arm," in *2019 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, 2019.

[105] R. Sato, M. Kamezaki, J. Yang, S. Sugano and H. Iwata, "Visual Attention to Appropriate Monitors and Parts Using Augmented Reality for Decreasing Cognitive Load in Unmanned Construction," in *The Abstracts of the international conference on advanced mechatronics : toward evolutionary fusion of IT and mechatronics : ICAM*, 2015.

[106] J. Yang, M. Kamezaki, R. Sato, H. Iwata and S. Sugano, "Inducement of visual attention using augmented reality for multi-display systems in advanced tele-operation," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Hamburg, 2015.

[107] A. Communications, "KIA MOTORS adds value to production plant infrastructure with Axis network cameras," Axis Communications, [Online]. Available: https://www.axis.com/ja-jp/customer-story/113. [Accessed 31 1 2022].

[108] H. G. Debarba, E. Molla, B. Herbelin and R. Boulic, "Characterizing embodied interaction in First and Third Person Perspective viewpoints," in *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, Arles, 2015.

[109] W. Zhou, J. Zhu, Y. Chen, J. Yang, E. Dong, H. Zhang and X. Tang, "Visual Perception Design and Evaluation of Electric Working Robots," in *IEEE International Conference on Mechatronics and Automation (ICMA)*, 2019.

[110] G. Andersen, "Focused attention in three-dimensional space," *Perception & Psychophysics,* vol. 47, pp. 112-120, 1990.

[111] Z. J. He and K. Nakayama, "Visual attention to surfaces in three-dimensional space," *Proceedings of the National Academy of Sciences,* vol. 92, no. 24, pp. 11155-11159, 1995.

[112] C. HTC, "HTC VIVE," HTC Corporation, [Online]. Available: https://www.vive.com/fr/product/. [Accessed 31 1 2022].

[113] S. Nagata, "Visual sensitivities to cues for depth perception," *The Journal of the*

Institute of Television Engineers of Japan, vol. 31, no. 8, pp. 649-655, 1977.

[114] A. D. Wilson and S. Golonka, "Embodied Cognition is Not What you Think it is," *Frontiers in psychology,* vol. 4, no. 58, 2013.

[115] A. Bender, H. Filmer, C. Naughtin and P. E. Dux, "Dynamic, continuous multitasking training leads to task-specific improvements but does not transfer across action selection tasks," in *Science Learn*, 2017.

[116] D. J. Simons, W. R. Boot, N. Charness, S. E. Gathercole, C. F. Chabris, D. Z. Hambrick and E. A. Stine-Morrow, "Do “Brain-Training” programs work?," *Psychol Sci Public Interest,* vol. 17, no. 3, pp. 103-186, 2016.

[117] S. CHARRON and E. KOECHLIN, "Divided Representation of Concurrent Goals in the Human Frontal Lobes," *Science,* vol. 328, no. 5976, pp. 360-363, 2010.

[118] B. Wahn and P. König, "Is attentional resource allocation across sensory modalities task-dependent?," *Advances in Cognitive Psychology,* vol. 13, no. 1, pp. 83-96, 2017.

[119] N. Nishida, Y. Iwasaki, F. Kato, G. Ganesh and H. Iwata, "Research on the embodiment of augmented bodies -The effect of active control and hand direction feedback of wearable robot arm on the sense of body width-," in *第26回日本バーチャルリアリティ学会大会論文集*, 2021.

[120] P. Kieliba, D. Clode, R. O. Maimon-Mor and T. R. Makin, "Robotic hand augmentation drives changes in neural body representation," *SCIENCE ROBOTICS,* vol. 6, no. 54, 2021.

[121] "VRChat," VRChat Inc., [Online]. Available: https://hello.vrchat.com/. [Accessed 31 1 2022].

[122] M. González-Franco, D. Pérez-Marcos, B. Spanlang and M. Slater, "The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment," in *2010 IEEE Virtual Reality Conference (VR)*, Boston, 2010.

[123] L. Brown, R. Doole and N. Malfait, "The Role of Motor Learning in Spatial Adaptation near a Tool," *PLoS ONE,* vol. 6, no. 12, p. e28999, 2011.

[124] MultiPRESENCE®, "Telecollaboration software / teleconsultation," MultiPRESENCE®, [Online]. Available: https://healthmanagement.org/products/view/telecollaboration-software-teleconsultation-multipresence-r-intouch-health. [Accessed 31 1 2022].

[125] M. M. Padrick and e. al., "COVID-19 Impact on Acute Ischemic Stroke Treatment at 9 Comprehensive Stroke Centers across Los Angeles," *Cerebrovasc Dis,* vol. 50, no. 6,

pp. 707-714, 2021.

[126] I. TELEXISTENCE, "Model-T," [Online]. Available: https://tx-inc.com/ja/technology-jp/. [Accessed 31 1 2022].

[127] C. Kempgens, G. Loffler and H. Orbach, "Set-size effects for sampled shapes: experiments and model," *Frontiers in Computational Neuroscience,* vol. 7, no. 67, 2013.

[128] K. R. Dobkins and R. G. Bosworth, "Effects of set-size and selective spatial attention on motion processing," *Vision Research,* vol. 41, no. 12, pp. 1501-1517, 2001.

[129] E. Abrahamse, J.-P. van Dijck and W. Fias, "How Does Working Memory Enable Number-Induced Spatial Biases?," *Front. Psychol,* vol. 7, no. 977, pp. 1-11, 2016.

[130] N. Cowan, "The Magical Mystery Four: How Is Working Memory Capacity Limited, and Why?," *Curr Dir Psychol Sci.,* vol. 19, no. 1, pp. 51-57, 2010.

[131] E. Rose, "Continuous Partial Attention: Reconsidering the Role of Online Learning in the Age of Interruption," *Educational Technology,* vol. 50, no. 4, p. 41–46, 2010.

[132] Y. Iwasaki, K. Ando, S. Iizuka, M. Kitazaki and H. Iwata, "Detachable Body: The Impact of Binocular Disparity and Vibrotactile Feedback in Co-Presence Tasks," *in IEEE Robotics and Automation Letters,* vol. 5, no. 2, pp. 3477-3484, 2020.

[133] E. G. Rieffel, A. Girgensohn, D. Kimber, T. Chen and Q. Liu, "Geometric Tools for Multicamera Surveillance Systems," in *2007 First ACM/IEEE International Conference on Distributed Smart Cameras*, 2007.

[134] P. M. Roth, V. Settgast, P. Widhalm, M. Lancelle, J. Birchbauer, N. Brändle, S. Havemann and H. Bischof, "Next-generation 3D visualization for visual surveillance," in *2011 8th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*, 2011.

[135] G. Lin and S. Carlile, "Costs of switching auditory spatial attention in following conversational turn-taking," *Frontiers in neuroscience,* vol. 9, no. 124, pp. 1-11, 2015.

[136] Z. O. Toups, N. Lalone, S. A. Alharthi, H. N. Sharma and A. M. Webb., "Making Maps Available for Play: Analyzing the Design of Game Cartography Interfaces," *ACM Transactions on Computer-Human Interaction,* vol. 26, no. 5, pp. 1-43, 2019.

[137] K. Nakabayashi, Y. Iwasaki and H. Iwata, "Development of Evaluation Indexes for Human-Centered Design of a Wearable Robot Arm," in *Proceedings of the 5th International Conference on Human Agent Interaction (HAI '17)*, New York, 2017.

[138] L. Drohne, K. Nakabayashi, Y. Iwasaki and H. Iwata, "Design Consideration for Arm Mechanics and Attachment Positions of a Wearable Robot Arm," in *2019 IEEE/SICE International Symposium on System Integration*, Paris, 2019.

List of research achievements for application of Doctor of Engineering, Waseda University

Full Name：岩﨑　悠希子　　seal or signature

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Journal論文	
○	"Detachable Body: The Impact of Binocular Disparity and Vibrotactile Feedback in Co-Presence Tasks", IEEE Robotics and Automation Letters, vol. 5, no. 2, pp.3477-3484, 2020, **Y. Iwasaki**, K. Ando, S. Iizuka, M. Kitazaki and H. Iwata.
	"3D Head Pointer: A manipulation method that enables the spatial position and posture for supernumerary robotic limbs", ACTA IMEKO, vol. 9, no. 1, pp.1-10, 2020, J. Oh, F. Kato, **Y. Iwasaki**, H. Iwata.
査読付国際会議論文	
○	"Comparison of Operating Method of Extra Limbs in Dual Tasks: Point and Path Instruction", Proceeding of the IEEE/SICE International Symposium on System Integration (SII'22), 2022, **Y. Iwasaki**, S. Takahashi, H. Iwata.
○	"Experiment Assisting System with Local Augmented Body (EASY-LAB) for Subject Experiments under the COVID-19 Pandemic", ACM SIGGRAPH 2021 Emerging Technologies (SIGGRAPH'21), no. 11, pp.1-4, 2021, **Y. Iwasaki**, J. Oh, T. Handa, A. A. Sereidi, V. Vimolmongkolporn, F. Kato, H. Iwata.
○	"Ubiquitous Body: Effect of Spatial Arrangement of Task's View on Managing Multiple Tasks", Augmented Humans Conference 2021 (AHs'21), Association for Computing Machinery, pp.40-44, 2021, **Y. Iwasaki** and H. Iwata.
	"Development of a Cooperative Work Method Based on Autonomous Learning of Implicit Instructions", Proceedings of the 11th Augmented Human International Conference (AH'20), no. 9, pp.1-8, 2020, L. Guinot, **Y. Iwasaki**, S. Takahashi and H. Iwata.
○	"Haptic Feedback System of the Additional Hand Position for Multiple Task Situations Using a Wearable Robot Arm", 2019 IEEE International Conference on Cyborg and Bionic Systems (CBS'19), pp. 247-252, 2019, **Y. Iwasaki**, K. Ando and H. Iwata.
	"Development of a three-fingered jamming gripper for corresponding to the position error and shape difference", 2019 IEEE International Conference on Soft Robotics, pp.137-142, 2019, K. Amano, **Y. Iwasaki**, K. Nakabayashi, H. Iwata.
	"Experimental Evaluation of Cooperativeness and Collision Safety of a Wearable Robot Arm", Proceeding of the IEEE/SICE International Symposium on System Integration (SII'19), 2019, L. Drohne, K. Nakabayashi, **Y. Iwasaki**, H. Iwata.
○	"A face vector - the point instruction-type interface for manipulation of an extended body in dual-task situations", 2018 IEEE International Conference on Cyborg and Bionic Systems (CBS'18), pp. 662-666, 2018, **Y. Iwasaki** and H. Iwata.
	"Experimental Evaluation of Cooperativeness and Collision Safety of a Wearable Robot Arm", Proceeding of the 27th IEEE International Symposium on Robot and Human Interactive Communication (ROMAN'18), pp. 1026-1031, 2018, K. Nakabayashi, **Y. Iwasaki**, S. Takahashi, H. Iwata.
	"Development of Evaluation Indexes for Human-Centered Design of a Wearable Robot Arm", 5th International Conference on Human-Agent Interaction (HAI'17), pp.305-310, 2017, K. Nakabayashi, **Y. Iwasaki**, H. Iwata.

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査読付国内講演会 ○	”随意操作が可能な【第三の腕】に関する研究 ～第二報：デュアルタスク状態における顔面ベクトルを用いた目標物支持性の検証～”, 第22回ロボティクスシンポジア, SICE/JSME/RSJ共同主催, pp.219-220(paper no.4B1), 2017, **岩﨑悠希子**, 岩田浩康.
国際講演会	"Development of an Eyeglasses-type Face Vector Acquisition Interface for Hands-free Control of a Third Arm", 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS’18), 2018.9, S. Takahashi, **Y. Iwasaki**, H. Iwata. "Research on the Third Arm: proposal of a face vector interface for voluntary and intuitive control of a wearable robot arm", 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS’17), 2017.9, **Y. Iwasaki**, H. Iwata.
国内講演会	"被験者実験の遠隔実施を目的とした非対面型指導システムの提案"，第26回バーチャルリアリティ学会大会，1D2-6, 2021，**岩﨑 悠希子**，王 卓毅，半田 匠，AlSereidi Ahmed，Vimolmongkolporn Vitvasin，加藤 史洋，岩田 浩康. "拡張身体の身体化に関する研究 ー第一報：装着型ロボットアームの能動制御と手先方向提示による身体幅感覚への影響ー"，第26回バーチャルリアリティ学会大会，1C3-7，2021，西田 野々香，**岩﨑 悠希子**，加藤 史洋，ゴウリシャンカー・ガネッシュ，岩田 浩康. "拡張身体へのAgency, Ownership誘発を目指した筋電制御システムと力触覚FBデバイスの開発"，日本機械学会ロボティクス・メカトロニクス講演会(Robomech2021)，2P3-E03，2021，西田 野々香，**岩﨑悠希子**，王卓毅，半田匠，加藤史洋，ゴウリシャンカー・ガネッシュ，岩田浩康. "拡張身体の姿勢推定のための振動子を用いた疑似固有感覚フィードバックシステムの効果" 第48回 日本バイオフィードバック学会学術総会，拡大セッション 一般演題1，2021，**岩﨑悠希子**、安藤孝三、岩田浩康. "人とロボットの協調作業における阿吽動作の成立条件の検証 —VR餅つきを題材に—" 第21回計測自動制御学会システムインテグレーション部門講演会（SI’20），paper no. 2D1-02, 2020.12, 安藤 孝三，**岩﨑 悠希子**，加藤 史洋，岩田 浩康. "直感的な随意操作が可能な【第三の腕】に関する研究 -拡張身体に対する空間定位のためのHead Bobbing式深度指示IF-", 日本機械学会ロボティクス・メカトロニクス講演会(Robomech2020)，paper no.2A1-C07，2020.5, 王　卓毅，**岩﨑悠希子**，安藤孝三，飯塚修平，Lena Guinot，半田　匠，岩田浩康. "拡張身体における不感帯を利用した2軸静的モーメントキャンセラーの開発", 日本機械学会ロボティクス・メカトロニクス講演会(Robomech2020)，paper no.2P1-C04，2020.5, 半田　匠，**岩﨑悠希子**，安藤孝三，飯塚修平，Lena Guinot，王　卓毅，岩田浩康.

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	"直感的な随意操作が可能な【第三の腕】に関する研究 -第12報：デュアルタスク環境下で使用可能な動作教示システムの検討-", 第40回バイオメカニズム学術講演会SOBIM2019, paper no. 2b3-2, 2019.12, 王卓毅, **岩崎悠希子**, 安藤孝三, 飯塚修平, 岩田浩康. "直感的随意操作が可能なDetachable Bodyに関する研究 -第三報:共在的視認を実現する視界提示手法の比較検討-", 第37回日本ロボット学会学術講演会(RSJ'19), paper no. 1E3-03, 2019.9, 飯塚修平, 安藤孝三, **岩崎悠希子**, 岩田浩康. "直感的随意操作が可能なDetachable Bodyに関する研究 -第二報:共在的作業における同時知覚システムの提案-", 第37回日本ロボット学会学術講演会(RSJ'19), paper no. 1E3-02, 2019.9, **岩崎悠希子**, 安藤孝三, 飯塚修平, 岩田浩康 "直感的な随意操作が可能な【第三の腕】に関する研究 -第十一報:内封される粉体に応じた把持特性および把持力の検証-", 第37回日本ロボット学会学術講演会(RSJ'19), paper no. 1E3-04, 2019.9, 天野浩平, **岩崎悠希子**, 岩田浩康. "【第三の腕】の駆動に伴う装着者への身体的作業負荷を軽減可能なキャンセラーの検討", 第26回バイオメカニズムシンポジウム, 2019.7, **岩崎 悠希子**, 中林 幸輝, 天野 浩平, 岩田 浩康. ”直観的随意操作が可能なDetachable Body に関する研究 第一報：共在的作業の重畳視認に好適な映像透過比率の検証”, 日本機械学会ロボティクス・メカトロニクス講演会, paper no.2A2-L04, 2019.6, 飯塚修平, **岩崎悠希子**, 岩田浩康. ”直観的な随意操作が可能な【第三の腕】に関する研究 第10報：手先位置を同定可能な Haptic Feedback Belt の開発と同定精度検証”, 日本機械学会ロボティクス・メカトロニクス講演会, paper no.2P2-H03, 2019.6, 安藤孝三, **岩崎悠希子**, 岩田浩康. ″直感的な随意操作が可能な【第三の腕】に関する研究第9報：身体的作業負荷の軽減のための重心補償機構の設計評価″, 第19回計測自動制御学会システムインテグレーション部門講演会（SI2018）, paper no.3A4-14, 2018.12, 中林幸輝, **岩崎悠希子**, 岩田浩康. "直感的な随意操作が可能な【第三の腕】に関する研究ー第八報：“Detachable Body”のコンセプトデザインー", 第36回日本ロボット学会学術講演会, paper no. 1B2-03, 2018.9, **岩崎悠希子**, 中林幸輝, 高橋翔太, 飯塚修平, 天野浩平, 安藤孝三, 岩田浩康 ”直感的な随意操作が可能な【第三の腕】に関する研究—第七報：搭載動作機能の照合に要する認知的負荷の分析—”, LIFE2018, paper no.2-4-1-2, 2018, **岩崎悠希子**, 岩田浩康. 【他6報】
その他 査読付国際会議論文	"Interaction with the Mercurial Robot: Work Assisting Robot Express the Tiredness", Proceedings of the 2019 2nd International Conference on Electronics, Communications and Control Engineering (ICECC'19), pp.29-33, 2019, **Y. Iwasaki**, K. Gushima, E. Tamaki.
受賞	Best Presentation Award, the 2019 2nd International Conference on Electronics, Communications and Control Engineering, 2019.4