

Evaluating the Impact of Image Delays on the Rise of MMI-Driven Telemanipulation Applications: Hand-Eye Coordination Interference from Visual Delays during Minute Pointing Operations

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Abstract

Robots with high freedom of movement can be used for minute manipulation, enabling a wide range of real-world applications. However, the use of telemanipulation systems driven by man-machine interaction (MMI) is currently limited to experimental trials, partly because the image delay during transmission interferes with the operator's hand-eye coordination. This study examined how delays affect operation efficiency by pointing target size, and the degree of difficulty when performing telemanipulation operations. We conducted tests in which subjects performed pointing operations while visual delays interfered with their hand-eye coordination. Our findings show statistically that regardless of target size, delay variance of 200 ms or less hardly affects operation efficiency, and that difficulty increases for a target diameter of between 4 and 2 mm.

Keywords: *MMI-Driven Telemanipulation; Image Delay; Hand-Eye Coordination; Minute Pointing; Operation Efficiency*

1. Introduction

Recent advances in robotics technology and ICT (information and communication technology) have enabled telemanipulation driven by man-machine interaction (MMI) using robots with high freedom of movement. Robot-driven telemanipulation is gaining attention for the potential it has to enable work in places unsuited to operators such as disaster-stricken areas or extreme environments. It is an area with a wide range of potential applications that could solve real-world problems such as ensuring operators' safety and creating more balanced distributions of human resources.

For example, medical services provided to users around the world can vary widely in quality and quantity since the concentration of medical resources available varies according to the size of cities in which hospitals are located. With their greater population density, larger cities tend to have greater concentrations of various resources. Since this trend is natural, it calls for effective use of the medical resources of large cities rather than attempts to forcibly correct differences through political measures. In this regard, advances in research on telemanipulation could provide a way to supplement human medical resources in places where they are lacking, such as in Japan's *genkai shūroku* (remote villages on the brink of extinction due to their aging populations).

Combining the functions of remote transmission (communications) and manipulation (robotics) enables composite functions for which several real-world applications have been announced. For example, these functions could be applied to conventional surgery to match telesurgery needs to doctors with the required skills. Remote transmission could also be applied to education, enabling doctors in cities to remotely provide skill education to doctors in remote areas [1]-[4]. These possibilities are therefore creating growing expectations that telesurgery and other telemanipulation applications will become a practical reality [5].

A past study has examined telesurgery using an experimental MMI-driven surgery robot [6]. As the world's first demonstration of telesurgery, it represents a major breakthrough and has had a major impact on medical professionals. However, telesurgery has not achieved widespread use. One reason is that surgery

imposes severe restrictions on operation precision and operation time, so it is not enough to merely show that remote robotic surgery that was once impossible is now possible.

The major problem with remote robotic manipulation for applications such as telesurgery is that a visual delay arises between the work sites. Telemanipulation is an activity requiring the operator to manipulate objects using visual information presented on a monitor. Therefore, the visual delay arising from the transmission delay has a major effect on operation efficiency and operation precision.

Before MMI-driven telemanipulation can achieve widespread use, researchers will need to quantify the maximum amount of delay that can be tolerated without affecting operation efficiency (which also affects safety), and how minute the operation can be before the delay makes efficient operation difficult.

Accordingly, this study examined visual delay (which affects arm positioning), and pointing target size (which corresponds to arm positioning precision). For each of several target sizes, we attempted to find the range of visual delay times (the operation efficiency range) over which operation efficiency can be considered the same, and the target size threshold at which operator positioning efficiency declines sharply.

2. Effects of Visual Delays on Arm Positioning

To provide background information for this study, this section describes the problems related to movement disturbances caused by a delay in the image. It discusses prior studies that have tried to reduce the transmission delay, and prior studies that have examined the movement problems that the delay creates. We describe the validity of the test parameters, the psychological approach used for testing, and the study results and observations, quantitatively demonstrating the effect of a visual delay on telemanipulation.

2.1 Hand-eye coordination

Humans perceive and evaluate stimuli from the outside environment, applying the results to body movements. This process of applying perceptually generated information to ongoing movement control is called hand-eye coordination [7]. Surgery was previously mentioned as a typical example of a telemanipulation application. It too is a process involving movement of the hands and arms relying on hand-eye coordination.

The most important aspect of coordinated movement is the temporal integration of the perception of the sensory organs. One fundamental task for arm movement is pointing—the task of moving the arm from starting coordinates and positioning it at target coordinates. Pointing includes the process of converting external

coordinates obtained by vision into internal body coordinates.

Hand-eye coordination functions by integrating systems such as vision and the somatosensory system. The hand arrival process driven by hand-eye coordination is composed of two types of movements: feedforward movements (which are ballistic movements) and feedback movements (which are corrective movements).

For the task of pointing (one type of arm positioning movement), the precision of feedback movements is an important element in enabling the operator to perform positioning accurately. Tasks such as surgery that require minute positioning are particularly prone to effects from visual delays. Therefore, disturbances to hand-eye coordination reduce operation efficiency during pointing operations in environments designed for remote robotic work controlled by an operator, such as master-slave systems.

A reduction in operation efficiency caused by a visual delay means a delay in the progress made during the scheduled operation time. Since the operation being performed will often have time constraints, the operator will often need to boost operation efficiency in subsequent processes, increasing the operator's psychological burden and risk factors such as process errors. This tendency is particularly marked in tasks such as telesurgery that involve minute operations and pressing time constraints. The next section presents prior studies on amounts of visual delay during telemanipulation, and discusses how delays affect ease of operation.

2.2 Prior studies

Since telemanipulation is performed by an operator relying on visual information presented on a monitor, a delay in the image arising from a transmission delay is a major impediment to working. Transmission delays are usually caused by three factors: (1) the communication line's transmission delay, (2) the processing delay caused by information compression and extraction, and (3) the response time of the actuators that move the robot. The transmission line delay is the longest delay of the three.

Prior studies on telesurgery have reported various total delay values. The total delay reported for the world's first demonstration of telesurgery previously cited was 155.0 ms⁶. Studies of telesurgery in Asia have reported total delays of 278.3 ms [8] and 582.4 ms [9]. The amount of delay during telemanipulation depends on several different elements, such as the communication path, transmission format, video device compression/extraction process, and robot reaction time. Previous tests in low latency mode have set visual delays of up to 640 ms since delays of 700 ms or longer make it difficult to temporally integrate the eyes and hands. Smooth movements become impossible at delays of this length, and the adoption of a 'wait-and-

move' strategy [10] is needed to enable accurate movements.

2.3 Effects of visual delays on hand-eye coordination

We have reviewed how hand-eye coordination is an important element for enabling smooth performance of an operation, and how temporal sensory integration of visual information and somatic sensation is important for the smooth working of hand-eye coordination. Then, what type of effect does a visual delay generated by remote transmission have on hand-eye coordination during arm movement? This section discusses this issue.

A prior study on the relationship between visual delays and somatic sensation has shown a sharp deterioration in operation efficiency resulting from environments introducing delays of up to 500 ms [11]. Visual delays of 700 ms or longer have been reported to result in test subjects adopting a 'wait-and-move' strategy to perform movements and smooth movements becoming impossible [10].

However, studies on operations performed with visual delays have not adequately described the effect of target minuteness on operation efficiency, or the minuteness threshold at which the operation efficiency of an operator declines. This study tested the efficiency of pointing tasks performed with visual delays of up to 600 ms (the maximum delay for which smooth movements can be expected). The study method below was used to describe this area.

3. Study Method

For each of several pointing target sizes, the aim of this study was to find the range of visual delay variance over which difference in operation efficiency can be considered significant, and the target size threshold at which operator positioning efficiency declines sharply. To achieve this aim, we needed to quantitatively reproduce the visual delays experienced during telemanipulation on an MMI-driven master-slave system. This section describes the placement of the test apparatus used to reproduce the delays experienced during telemanipulation, describes the operating principle of the image delay generator used, and presents the test plan used to measure performance in the visually delayed environment.

3.1 Test apparatus placement

Figure 1 shows the placement of the test apparatus used for testing. The image of the work area was photographed by a video camera and transmitted to a monitor via a delay generator. Using this apparatus configuration, the visual delay generated between the master and slave in a telemanipulation environment was reproduced on the

monitor and used for pointing tasks in the work area. The camera and monitor used were commercial models with short processing delays, minimizing the amount of uncontrolled visual delay generated. The amount of delay presented when the delay generator was set to its minimum delay amount was 98 ms.

To determine the causal relationship between image delays and ease of operation, we controlled distances to keep the visual distance (the distance from the eyes to the monitor display surface) the same as the distance from the work area to the monitor. We also adjusted the size of the pointing targets displayed on the monitor to make them actual-size. The camera was placed in a position away from the test subject's eye line to prevent it from becoming a distraction. Efforts were also made to minimize external disturbances caused by differences from normal sensory experiences.

3.2 Test apparatus and measuring instruments

Table 1 lists the test apparatus and measuring instruments this study used to describe the effect of visual delays on pointing.

Since the aim of this study was to describe the effect of visual delays on ease of operation, the test administrators took steps to ensure a user-friendly environment for test subjects by quantitatively controlling factors such as the distance from the test subject to the monitor, and the size of the targets displayed on the monitor.

Taking surgery as a representative example of the minute pointing operations examined by this study, we devised a simple manual dexterity model of surgery for our examination of minute tasks.

Our simple manual dexterity model reproduced the positioning movements and target minuteness of actual surgery. To set minuteness, we set the size of the dot targets used by considering the average size of dot-target blood vessels and mucosae. To set positioning movement directions, we placed the dot targets so that directions of positioning movements would be as random as possible. We set the maximum distance between targets at 150 mm after interviewing hospital staff to determine the range of movements performed during surgery, and considering factors such as range of wrist movement.

Our simple manual dexterity model consisted of circular dot targets used to recreate pointing minuteness.

The targets were placed on the vertices of a regular pentagon with sides of 100 mm in length. Three model difficulty levels were used, each having a different target diameter (2, 4, or 6 mm). Figure 1 shows the sequence of dots. Operation time was measured in hundredths of a second, and measured time data was rounded to the nearest tenth of a second to create the analysis data.

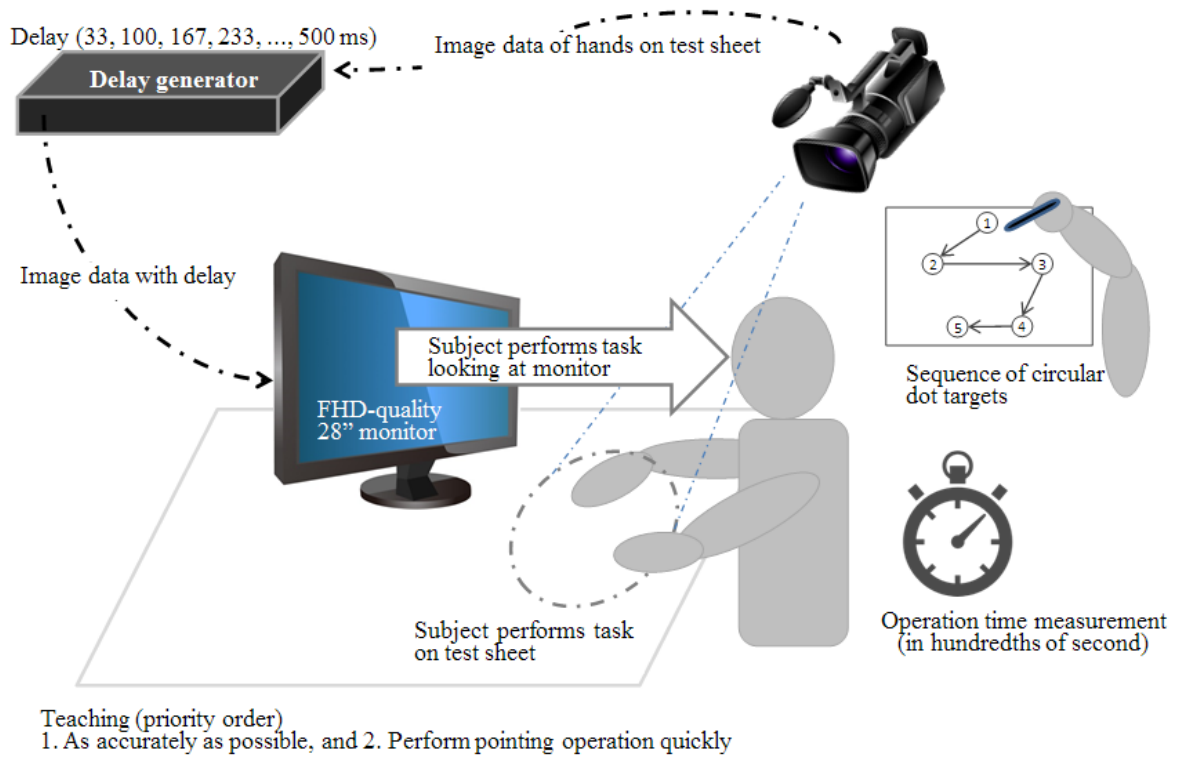


Fig. 1 Test apparatus configuration

Table 1: Test and measurement equipment

	<i>Item</i>	<i>Manufacturer and model</i>	<i>Comments</i>
Test equipment	Camera	Astro AH-4410-A	Full High Definition (FHD) (60i) output
	Monitor	IBM T221	28-inch FHD monitor
	Delay generator	[Created by authors]	For image delay (1 to 15 frames)
Measurement equipment	Simple manual dexterity model	[Created by authors]	<ul style="list-style-type: none"> • Circles of 2, 4 or 6 mm in diameter • Circular dot targets placed at vertices of regular pentagon with sides of 100 mm
	Stopwatch	Casio HS-80TW	Can measure thousands of second

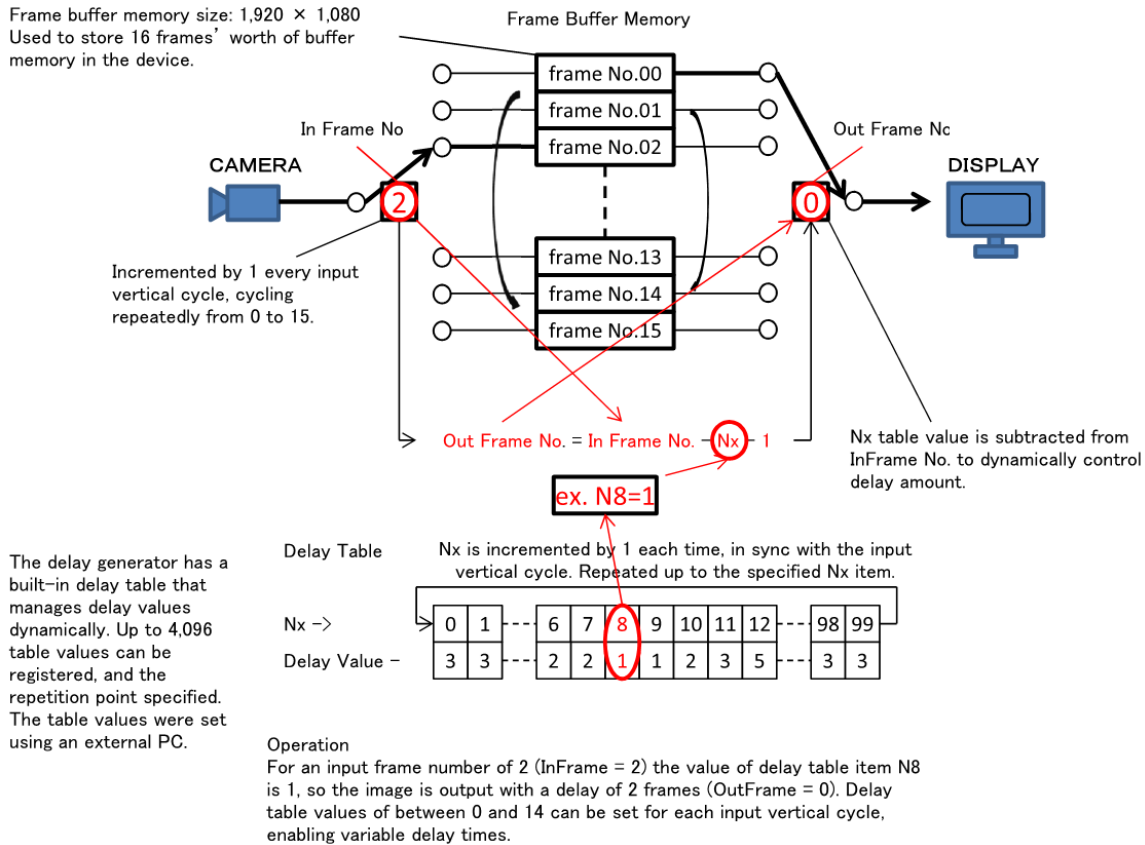


Fig. 2 Delay generator operating principle

3.3 Operating principle of image delay generator

Since the aim of this study was to precisely evaluate the effect of an image delay, a function to quantitatively control the image for presentation on the monitor was an indispensable requirement. To meet this requirement, we created our own image delay generator for this study. To enable test conditions to be set precisely and minimize the processing delay, we used highly responsive RAM (random access memory) as the memory medium for temporary storage of the image. Using this basic design, we created an image delay generator that controlled the image frame by adding a buffer to the internal memory storing the image data. Figure 2 illustrates the principle used to generate delays.

Our delay generator was able to create delays ranging from 1 frame (33 ms) to 15 frames (500 ms), in 1-frame increments. During the design phase, we set the maximum amount of delay not requiring delay compensation for telemanipulation at 500 ms (15 frames).

The standard FHD frame size of 1,920 × 1,080 was input, with the newest frame replacing the last frame. The image

reproduced the visual delay experienced during telemanipulation by being output with a delay from the current frame equal to the number of frames set by the test administrator.

3.4 Test plan

The aim of this study was to precisely evaluate the effect of image delays and assess the outlook for the rise of MMI-driven telemanipulation applications. Describing operation efficiency in terms of visual delay levels and dot size differences was indispensable for achieving this aim. We therefore set three groups of dot sizes as variables (2, 4, and 6 mm in diameter), and tried to eliminate individual differences in movements between test subjects by using a random dot placement for every 10 subjects. The image presentation stimulus had 8 delay levels (33, 100, 167, 233, 300, 367, 433, and 500 ms) for hand-eye coordination interference. To reduce the effect of learning on the presented stimulus, we conducted a total of 16 trials in which subjects were presented with a combination of two delay stimulus patterns having conditions of gradually increasing and decreasing delays. To minimize the effect

of fatigue, breaks of at least 1 minute were provided between each trial.

To determine operation efficiency and difficulty levels during pointing operations with visual delays, we performed the following two analyses: (1) We compared groups of the same dot size to determine the delay level at which operation time became sufficiently different. (2) We compared operation times for different dot sizes using the same delay level. The first analysis was performed by comparing each test subject to themselves. The second analysis was performed by comparing different test subjects.

To compare differences in delay level among and between test subject groups, we used multiplex analysis. We used Bartlett's test to check for equal variances. When equal variances could not be found, we selected the Friedman test or Kruskal-Wallis test (nonparametric test methods) to test the differences among different delay levels. Only when this analysis did not detect a significant difference for all processes, we used Scheffe's paired comparison (a type of multiplex analysis).

3.5 Test subjects

To enable precise evaluation of the effect of image delays on ease of operation, we needed to reduce external disturbances during testing. Right-handed males in their 20s with no visual abnormalities were used as the test subjects for this study.

3.6 Test procedure

Before starting the test, test subjects were instructed to complete the operations in as little time as they could manage while still pointing precisely and without errors, taking the operation efficiency of the remote environment into consideration. For ethical considerations, subjects were told they could stop the test if they felt unwell, and subject consent was received before testing started.

Each subject started the pointing operation at a start signal from the test administrator taking measurement. The operation consisted of pointing at (making contact with) the specified five points in the correct sequence. If a subject was unable to point within the circular border of a given target dot, he was not permitted to skip it and proceed to the next dot. He was required to successfully point at each dot before proceeding. To determine the effect of visual delays on positioning, the test administrator visually assessed whether contact had been made with each target dot and instructed the subject whether he was permitted to proceed to the next dot.

Ultimately, the time it took the subject to point at dots 1 to 5 was measured and counted as one trial.

4. Analysis Results

We performed two analyses for this study to quantitatively determine the effect of visual delays on arm positioning. One analysis was performed to determine the identification space of operation efficiency at various delay levels. The other analysis was done to identify the pointing difficulty threshold for minute pointing tasks. The analyses done for this study are described below.

4.1 Analysis 1: Differences in delay variance range for each dot size group

We used the test data obtained from the test plan and test subjects to determine statistically that there was little generalization in response to the presented stimuli. Next, we used Bartlett's test to check for equal variances, to determine the directionality of the statistical process. We found no equal variances, so used the Friedman test (a nonparametric test method) on different delay levels.

Testing at the 5% significance level for the degree of operation efficiency resulting from the amount of delay, we obtained a 1% significant difference. From this result, we inferred that we had ensured validity for performing multiplex analysis, and continued multiplex analysis. Since we compared a large number of levels for our tests (eight levels), we used Scheffe's paired comparison, which has a demanding detection rate for nonparametric multiplex comparisons. Our statistical analysis detected a 1% or 5% significant difference for delay level differences of between 8 and 10 or more frames for the 2, 4, and 6 mm diameter groups (Figures 3, 4, 5).

Figure 3 shows that for the 2 mm dot size group, operation time increased sharply as the amount of delay increased, with a sharper upward slope than for the 4 and 6 mm dot size groups. The delay variance range in operation efficiency for the 2 mm group was 200 ms. This range was 67 ms narrower than the range for the other groups (the 4 and 6 mm groups).

Figures 4 and 5 show that for the 4 and 6 mm dot size groups, operation times became longer as delays became longer. However, in terms of difficulty, the slopes of the graphs for the 4 and 6 mm dot size groups were nearly the same. The efficiency delay variance range in operation for these groups was 266 ms.

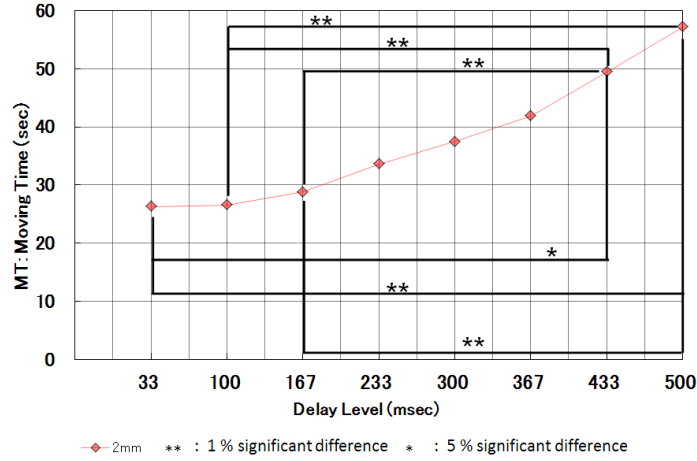


Fig. 3 Delay variance range in operation efficiency for 2 mm diameter group

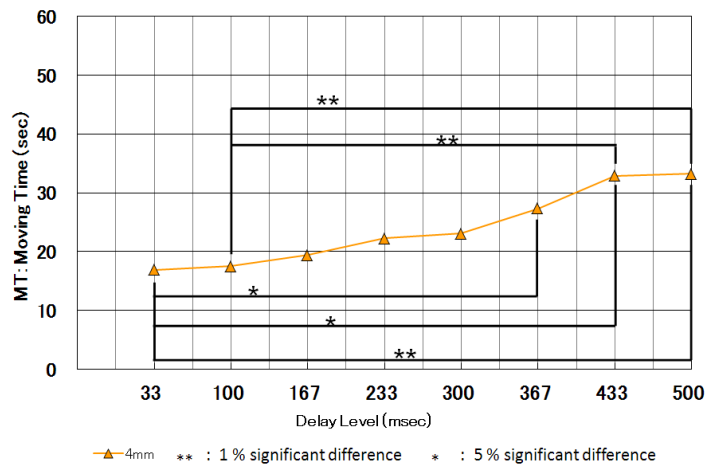


Fig. 4 Delay variance range in operation efficiency for 4 mm diameter group

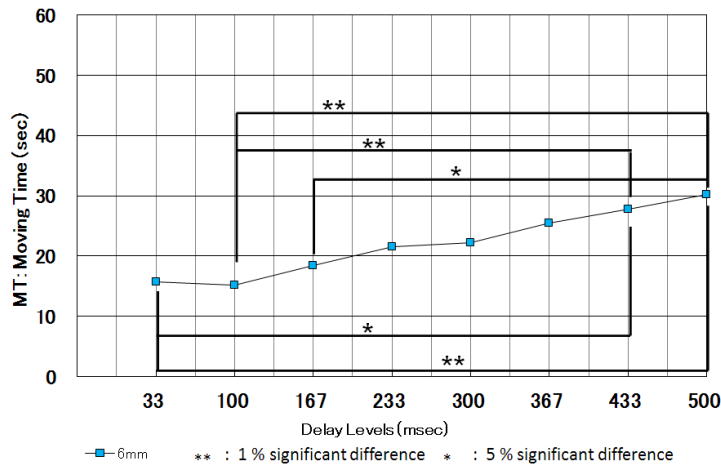


Fig. 5 Delay variance range in operation efficiency for 6 mm diameter group

4.2 Analysis 2: Dot size and target size threshold at which operation efficiency declines (group-to-group comparisons)

Figures 3, 4, and 5 show that there were large differences in operation time at the same delay level when comparing the 2 and 4 mm diameter groups to the 6 mm diameter group. The 4 and 6 mm diameter groups appear to have nearly no difference in operation time. We performed a statistical process to check whether this inference was correct. We found no equal variances using Bartlett's test, so for this analysis we used the Kruskal-Wallis test (a nonparametric test method) to test the differences among different delay levels.

For the Kruskal-Wallis test done at the 5% significance level for the effect that differences in delay level had on operation efficiency, we obtained a 1% significant

difference for the entire process. From this result, we inferred that we had ensured validity for performing multiplex analysis, and continued multiplex analysis. We used Scheffe's paired comparison for our tests.

Figure 6 shows the statistical analysis results. When the 2 and 6 mm dot size groups were compared using this analysis, 1% or 5% significant differences were found between all the delay levels. When the 2 and 4 mm dot size groups were compared, 1% or 5% significant differences were also found for half of the compared delay levels. We found no significant difference in operation time between the 4 and 6 mm dot size groups. These findings show statistically that for pointing tasks with delays, operation efficiency is affected by the set minuteness, and for target diameters of 4 to 2 mm, there is a threshold at which operation efficiency declines significantly.

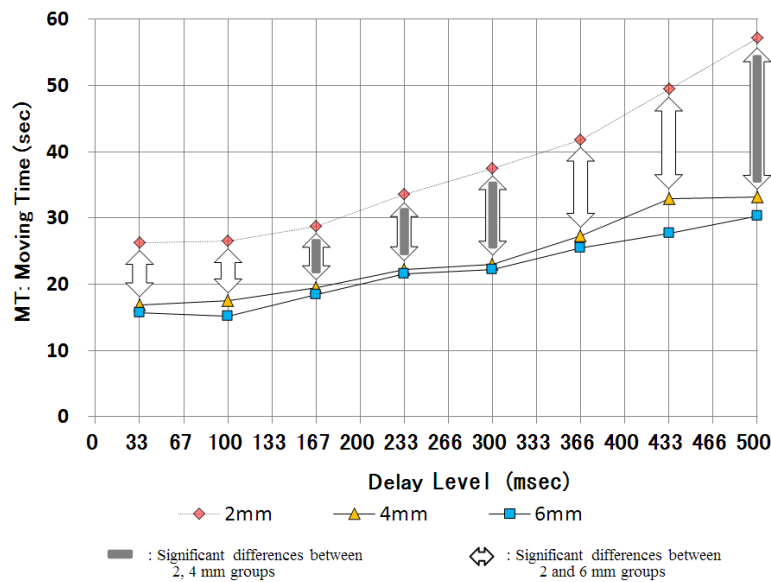


Fig. 6 Difference of difficulty between various target sizes at same delay levels

5. Test Discussion

This section discusses the aims of this study—the delay variance range for each dot size, and the target size threshold at which efficiency sharply declines.

5.1 Delay variance range for each dot size group

The key finding about the delay variance range for each dot size group is that regardless of dot size, significant differences in operation efficiency were detected only when there were delay level differences of 6 to 8 or more

frames. These frame delays correspond to a delay variance range of 266 to 333 ms. According to Fitts's law, the index of difficulty (ID) for a pointing task is given by $ID = \log_2(A/W + 1)$ [12]-[13], where A is the distance to the pointing target and W is the width of the target. As indicated by the formula, the index of difficulty increases as the target size becomes smaller. Fitts's law is also given as $MT = b(ID) + a$, indicating that movement time MT increases as the dot size becomes smaller. When a pointing task is performed using targets of the same size and within delay variance range described by this study, the findings of this study quantitatively suggest that the task will be

within the same operation efficiency at the 5% significance level.

5.2 Relationship between dot size and delayed pointing task difficulty

The key finding about the relationship between dot size and pointing task difficulty is that when each group was compared at the same delay levels, the 2 mm dot size group had significant differences in operation times relative to the 4 and 6 mm dot size groups. When the 4 and 6 mm dot size groups were compared at the same delay levels, no significant differences were detected. These findings quantitatively suggest that the threshold at which pointing tasks become difficult for humans owing to the effect of delays is between a dot size of 4 and 2 mm.

6. Conclusion and Future Outlook

This study examined the effect of delays (a major problem for MMI-driven telemanipulation) on the operation efficiency and difficulty of minute pointing tasks. We statistically showed that for each dot size group, regardless of target size, delay variance of 200 ms or less hardly affects operation efficiency.

When comparing the operation times for each dot size for the same delay levels, we found that statistically significant differences arose between the 2 mm dot size group and the other groups, thereby demonstrating that there is a wall of difficulty between a dot size of 4 and 2 mm.

These findings have enabled us to make a quantitative assessment that pointing tasks with delays have dot size-dependent difficulty differences, and to anticipate the outlook for the rise in MMI-driven telemanipulation when this information is applied to real-world applications.

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