

A Fundamental Study of Tool Embodiment for Human Dynamic Analysis Relating to Handling and Stability of Driving

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ABSTRACT

In the course of formulating methods for evaluating the handling and stability of driving an automobile, attention was focused on embodiments of the size of the automobile and its movements, which the operator absorbs into his or her own sensorimotor system. An experiment was devised to clarify the relationship between embodiment and sensorimotor activity. The experiment involved cutting paper with scissors in a virtual reality environment, where that action would be considered equivalent to steering an automobile from the perspective of processing sensorimotor system information.

In a virtual reality environment, the sensory quantity that accompanies activity is provided to the operator as feedback information. When this information was changed in various ways, the corresponding changes that occurred in the cerebral blood flow clarified the relationship between the feeling of actual operation generated during operation and the activity of the central nervous system. It was also found that the feeling of actual operation requires an appropriate sensory quantity to be presented, and that time delay in presenting the sensory quantity alters the feeling of actual operation. This experimentation during the manipulation of tools produced results that led to new ideas regarding evaluation of the handling and stability of driving of automobiles from the perspective of embodiment. In other words, it led to the proposal that it is necessary to evaluate the sensory information generated during driving.

1. Introduction

Automobiles and motorcycles have the basic capabilities to go, turn, and stop. Drivers operate these vehicles with the basic operations of providing driving power, steering, and braking. Or, for motorcycle riders, the basic operations would be providing driving power, distributing weight, and braking. Performance of the automobile or motorcycle in terms of movement according to the will of the operator is termed handling and stability of driving.

At present, quantitative evaluation of such performance in automobiles is carried out by the open-loop testing method, which looks only at the automobile, and closed-loop testing, which includes a simulated driver. In open-loop testing, movement is imparted to the automobile by means of the drive wheels, the steering system, and so on. For example, there are numerous reports of research on tire grip characteristics and simulations of vehicle movement⁽¹⁾. In closed-loop testing, on the other hand, research and development⁽²⁾ are underway on simulation technology for a driver model that is a simplified representation of a function model equipped with an input-output system that includes

a feedback loop for steering and other such operations. In closed-loop testing, robustness and other such positive and negative aspects of handling and stability of driving are evaluated from the cause-and-effect relationship between vehicle behavior and operation quantities.

Both these test methods involve the driver acting on the vehicle using prescribed methods of operation. The vehicle behavior that is generated is then quantized to be subjected to evaluation. Meanwhile, experimental systems to make quantitative observations of the driver have been designed in order to carry out the vehicle evaluation from the driver's viewpoint, and that is where handling and stability of driving have been verified using sensory evaluation, steering performance, and other such means⁽³⁾. However, the reason that the driver is able to judge the positive and negative aspects of vehicle behavior remains unexplained. In order to determine an explanation, the present research has focused on the driver's brain. Since the brain is an information processing organ, it would appear that the driver acquires some kind of vehicle information in conjunction with operation of the vehicle, and that the driver processes this information in the brain

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in order to arrive at some kind of evaluation. However, the characteristics of that information processing have not been examined. For the present research, therefore, a summary was made from presentations given to date regarding the relationship between sensorimotor information and sensory evaluation as explained by functional brain imaging and psychology experiments. This led to the concept that the perspective of sensory information provided to the driver is important in evaluating handling and stability of driving, and that concept will be described in the following.

2. Functional Brain Imaging of Sensory Information Quantities

The question here is what kind of information processing is performed by the driver's brain while driving? Driving an automobile is in effect like treating the automobile as a part of one's own body. In other words, when a driver has formed an embodiment with respect to the automobile, then the driver himself or herself is the bodily representation of the behavior in the traffic environment resulting from the movement of the driver's own hands and feet. Therefore the information processing is complex both conceptually and somatically. The conceptual aspect has to do with driving actions that can be verbalized, such as what route to take to what location at what time, what to do at the signal in the intersection, what kind of vehicle interval to maintain while driving, and so on. The somatic aspect has to do with driving actions, such as steering while feeling the lateral acceleration of the vehicle, stepping on the accelerator pedal while feeling the frictional force of the road surface, and so on. Even while driving, the control of vehicle behavior is this kind of somatic information processing⁽⁴⁾.

It is not easy, however, to make quantitative observations of some specific activity in the brain of a driver who is engaged in driving and, out of this complexity of information processing, to isolate only that information processing that is related to the sensorimotor system. Moreover, information processing in the brain has not been examined by anyone, so that the relationship, for example, between the magnitude of the lateral acceleration of a vehicle and driver operation or sensory evaluation remains unexplained. Controlling the disarrangement of driving posture caused by lateral acceleration while driving through a turn also constitutes information processing in the brain that involves the sensorimotor system. Even if the focus is placed on operation of the steering wheel in such a situation, there is a chance that other components of brain function will also end up being included in the measurement. Thus, it is not easy to separate out the multiplicity of brain function tasks that arise simultaneously in the same signal.

What requires attention in making quantitative observations of brain function, therefore, is how the tasks are framed. The aim of the present research is to begin by first laying a cornerstone. Attention was therefore focused on sensorimotor information processing during the activity

of tool operation that is qualitatively equal to the operation of an automobile. The experimental system described below was built and used to make quantitative observations of brain functions. An overview of that research will be given⁽⁵⁾.

2.1. Configuring an Experiment Qualitatively Equal to the Operation of an automobile

Functional brain imaging in a sensorimotor system requires comparative experiments in which research participants are presented with multiple types of sensory information. At the same time, when planning the experiment, as noted above, it is necessary to simplify the experiment in order to extract only sensorimotor system data from the complex information processing environment. It was decided, therefore, to use virtual reality (VR) technology to make the sensory information quantities variable. In order to reproduce qualitative equality with the operation of an automobile from the perspective of sensorimotor information processing even in a simplified experiment, an experiment using scissors to cut paper was planned.

The question of why operating an automobile and using scissors are qualitatively equal was addressed. In operating an automobile, the driver predictively establishes a line on which to drive over the route to the destination. In order to convert the power generated in the vehicle to movement, the driver turns the steering wheel, for example. The changes in physical quantities that constitute vehicle behavior are sensed by means of receptors, and movement proceeds while the driver makes adjustments in the amount of steering applied. Similarly in operating a pair of scissors, the user predictively establishes a course that the scissors will follow in order to cut out the envisioned shape. While sensing changes in resistance from place to place due to differences in paper thickness as well as differences in the fiber direction, the user engages in the work of connecting the cutting points along a line while adjusting the speed in opening and closing the scissors and the point of cutting action. Proceeding from this perspective, an experimental evaluation of sensorimotor information processing was performed with a focus on the qualitative equality of driving an automobile and operating scissors in terms of the following six items:

- (1) The tools are familiar;
- (2) The feedback is not instantaneous, as with the blows of a hammer, but is continuous during the operation;
- (3) The operation occurs through comparison of prediction and results;
- (4) The results along the way make up the course to the final objective;
- (5) The operation is carried out with care because errors could lead to injury; and
- (6) There is a double interaction: between the person and the object of operation, and between the object of operation and the outside world.

The work tasks were configured at four levels, with variations occurring only in sensory information relating to the cutting work. In other words, as shown in Table 1, there were these four tasks: the task of using real scissors to cut real paper (referred to below as the real scissors task); the task of opening and closing the right hand while wearing a sensor glove so as to use scissors drawn using computer graphics (CG) to cut CG paper in virtual reality (referred to below as the VR scissors task); the same task with the addition of the sound of cutting and a tactile vibration signal (referred to below as the VR scissors task with added auditory-tactile stimulus); and the task of observing VTR playback of recorded imagery showing another person performing the work of cutting in a real environment (referred to below as the VTR observation task).

The research participants were five right-handed adult males of the Mongoloid type. In their left hands, they held real paper and virtual paper that they drew toward themselves as if reeling it in. Tactile vibration signals were provided by vibrators placed at multiple locations on a glove, as shown in Fig. 1. The vibrators consisted of motors that rotated eccentrically placed weights to produce vibration. The research participants wore these gloves and made motions as though they were using a pair of scissors. As shown in Fig. 2, imagery of these hand movements was generated on-screen by CG.

2.2. Cerebral Blood Flow Imaging by NIRS and Experimental Protocol

Functional brain imaging was performed by observing changes in cerebral blood flow. When neuron clusters in the brain are active, arterial blood to the activated area increases in order to supply it with oxygen and sugar. Near Infrared Spectroscopy (NIRS) is able to observe the cerebral hemodynamics of oxyhemoglobin and deoxyhemoglobin, which have different light-absorbance properties, by directing near infrared light from the outside of the scalp and detecting the scattered light that returns from the brain. Hemoglobin is contained in the blood, so changes in hemoglobin concentration indicate changes in blood flow. When hemoglobin increases, its absorbance increases so that there is a decrease in the amount of scattered light detected. Although the simultaneous equations and other detailed information on this method will not be provided here, different amounts of scattered light are detected from oxyhemoglobin and deoxyhemoglobin at the multiple wavelengths of light to which they are exposed, and based on those values, relative changes in hemoglobin concentration can be calculated⁽⁶⁾. Sensors are placed from the forehead to the top of the head, distributed in a left-right symmetrical grid that has 24 sensors at 3 cm intervals. The experimental protocol calls for participants to perform 10 experimental blocks. For each block, they rest quietly with eyes closed for 20 seconds, then perform their tasks continuously for 20 seconds, immediately following which they again rest quietly with eyes closed for 20 seconds. The

Table 1 Experimental tasks for measurement of brain

	Real task	VR tasks		VTR observation task
Experimental scenarios				
	Real paper with real scissors	VR paper with VR scissors generated using sensor glove on right hand	Auditory and tactile sensory information added to task at left	Observing video recording of real task performed by someone else

blocks are separated by intervals of two to three minutes. Other tasks are presented to participants on different days at the same time of day, taking the influence of their circadian rhythm into consideration. The order in which tasks were presented was randomized and differed for each research participant.

In quantizing the changes in oxyhemoglobin concentration (ΔCoxy), the average of hemoglobin concentration changes in the period of 0-20 s was defined as the change in concentration for the period at rest. The average of hemoglobin concentration changes in the period of 20-40 s was defined as the change in concentration for the work period. Since each task is performed for 10 iterations, 10 sets of rest values and work values are



Fig. 1 Vibrators on right-hand glove. Five small motors are placed at circled locations on the tops of the fingers and one on the palm.

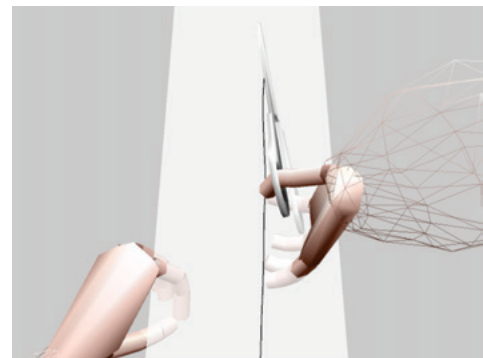


Fig. 2 VR environment with right and left hands, a pair of scissors, and a sheet of paper displayed by CG

calculated for each experimental level. These values were used to judge whether changes in hemoglobin concentration during work on tasks was significantly different from concentrations when at rest by conducting paired, two-tailed t-tests. Quantization of data on changes in hemoglobin concentration in the period of 40-60 s was used to eliminate drift components caused by imaging equipment.

2.3. Results from Analysis of Functional Brain Imaging

The area that showed conspicuous activation to a significant degree in all research participants during the real scissors task was the prefrontal area of the left hemisphere. Since the research participants were using the scissors with their right hands, the resulting activation in the left hemisphere was in agreement with findings to date that sensory input and motor output involve opposite hemispheres of the brain. The observation of activation in the prefrontal area during work is also in line with the findings of neuroscience, since the prefrontal area is said to govern the integration of movement and sensory information, and activation of this area would be expected with work that involves both motor output for opening and closing the scissors and sensory input of feedback information from receptors. On the other hand, no activation was observed around the prefrontal area of the left hemisphere in any research participants during the VTR observation task, and no common areas of activation were observed in imaging areas among the research participants. Neither were any common areas of activation observed in any of the research participants in either of the VR scissors tasks. In order to make a comparison across all tasks, therefore, the focus was placed on hemodynamics in the vicinity of the left prefrontal area where activation was observed during the real scissors task. The arithmetic mean of the change in oxyhemoglobin concentration in the vicinity of the left prefrontal area during this work was calculated for all the experimental subjects. According to ANOVA, the difference in magnitude between the two is $F(3,12)=6.712$ and $p<0.01$, suggesting that the difference is due to the difference in task. The results are shown in Fig. 3. The fact that the VR scissors task showed a greater change in blood flow by comparison with the VTR observation task in the vicinity of the left prefrontal area, where activation occurred with real scissors, suggested that the VR scissors task results in greater cerebral activity. The VR scissors task with auditory-tactile stimulus showed even greater change in blood flow and so suggested greater cerebral activity than the VR scissors task, which involved only the visual sense.

Before this imaging was carried out, the research participants were given opportunities to make trial runs of each task in order to become accustomed to it. At that time, the participants were asked to rank the tasks in order of the extent to which they felt real. All the research participants ranked the tasks in ascending order of feeling of reality from VTR observation task (lowest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and

real scissors task (highest).

Listing the tasks in order from smaller blood flow change to larger, they go from VTR observation task (smallest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and the real scissors task (largest), which is the same order of tasks in terms of the feeling of reality related above. The magnitude of blood flow indicates the degree of activation of the brain, which expresses the degree of information processing activity in the brain. This experiment allows for variation of the sensory information quantities, and it is also apparent that the feedback information in the sensorimotor system during the performance of the tasks increases in order of sensory information quantity, from the VTR observation task (lowest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and the real scissors task (highest). The results of this experiment, therefore, yielded the suggestion that information processing in the brain that integrates the abundance of work feedback information and physical activity is required in order to obtain the feeling of actual operation of a tool, or in other words, to obtain a response. The above are the experimental results relating to the presence or absence of sensory information quantities accompanying activity and to their magnitude.

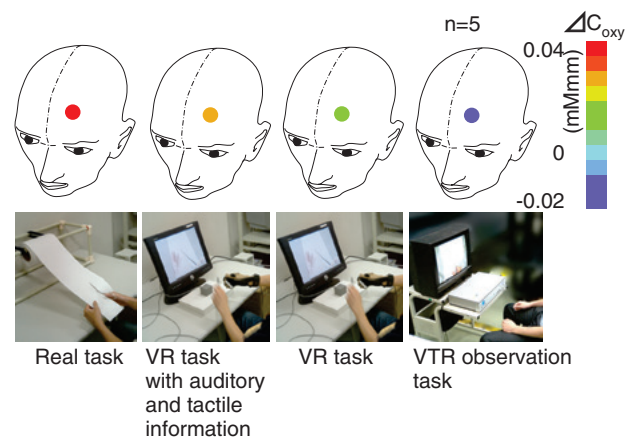


Fig. 3 Experimental result for measurement of brain activation

3. Evaluation of Time Delay in Manifestation of Sensory Information

Evaluation tests were conducted to determine what kind of operating impression the operators had regarding the time characteristics of sensory information, and those research results⁽⁷⁾ will be outlined next. The eight research participants were right-handed. At this point the VR scissors task with added auditory-tactile stimulus described in Chapter 2 was used as the basis for preparing a test environment in which the timing for presenting sensory information feedback to the research participants

was deliberately delayed. Even when the system is not specially configured for a delay in presentation, this VR experimentation system includes a delay of 50 ms that accompanies the sensor input, which occurs approximately 20 times per second, together with the various types of computation process and the drawing updates. There were four presentation test conditions of no delay (including the 50 ms), 200 ms, 500 ms, and 1000 ms. The VR system used for functional brain imaging described above was used with the no delay condition.

The experimental protocol has the research participants using VR scissors to cut the equivalent of 50 cm of VR paper under two of the four types of delay conditions. After the cutting work, they provide a comparison in terms of sensory evaluation. Using all combinations, there are six combinations of test conditions for paired comparison. Their order is randomized so that the order will vary with each research participant. Participants respond to the sensory evaluation using the following five levels regarding each combination of cutting work: (1) the operational feeling is better with the former delay environment; (2) the former is somewhat better; (3) there is no discernible difference; (4) the latter is somewhat better; and (5) the latter is better.

Since each delay was randomized, as described above, it was supposed that there was no order effect and the analysis was carried out using Scheffe's method of paired comparison with Nakaya's modification, in which the order is not shuffled. The results of analysis are shown in Table 2.

As shown in Table 2, no significant difference was found between the evaluation by research participants and the evaluation by combinations of delay conditions. However, a significant difference was found in the evaluations of delay conditions, with a significance level of 1%. The magnitude relations of those delay conditions, based on their statistical scores, are as follows. In terms of operational feeling, the no delay condition was best, followed by the 200 ms delay condition. Both these conditions yielded positive impressions. In terms of negative operational feeling, however, the 500 ms and 1000 ms delay conditions were cited, and the 1000 ms delay condition produced even more negative impressions.

In interviews conducted after the experiments, all the research participants indicated a similar tendency in their impression of operation with the 200 ms delay, using such expressions as, "It was sluggish," "It felt like I was cutting through something thick," "The scissors were stiff and their movement was slow," and so on. For this reason, half of the research participants responded that work under no delay conditions was "somewhat better." Under 500 ms and 1000 ms delay conditions, they related their impressions with such statements as "It wasn't possible to perform cutting operation in a normal manner, and that was very stressful," "It was difficult to cut in a straight line," "It felt as though I had become an old person," and so on. This showed that providing sensory information feedback generally simultaneously through a sensory organ elicits a positive

Table 2 Results of Scheffe's method of paired comparison with Nakaya's modification

Source	Sum of squares	Degree of freedom	Unbiased variance	F
Total	100	48		
Main effects	85.187	3	28.395	241.54
Main effects × personal	9.3125	21	0.4434	3.7721
Combination effects	0.5625	3	0.1875	1.5949
Error	4.9375	42	0.1175	

Here, $F(3,7,0.01)=8.451252 < 241.54$, $F(21,7,0.01)=6.132382 > 3.7721$, $F(3,42,0.01)=4.285255 > 1.5949$

operational feeling, and, on the other hand, that a longer time interval from when the operation is completed to when sensory information is obtained makes the operation itself difficult to perform or gives the impression that the tool being operated, or the object of operation, or even the operator has somehow deteriorated or changed into something different.

4. Evaluation of Sensory Information

In the research introduced in Chapter 2, the research participants simultaneously experienced both tactile and auditory sensory information. The question then is how the different kinds of sensory information affected the operating impression. The following will provide an overview of research on the relationship between sensorimotor information and the operating impression⁽⁸⁾.

4.1. Relationship between Tactile Stimulus and Operating Impression

The experiment introduced here involved cutting in the VR system, described above, carried out under the no delay condition, which includes a 50 ms delay, and without any cutting sound, meaning without any auditory signal. The tactile vibration signal provided during VR scissors operation was in three levels of intensity. Five sets of tactile vibration signals of different intensities were prepared according to the fingers or palm area where the vibration sensation was to be provided. Given the earlier examination results obtained prior to this experiment, the tactile vibration feeling was assigned three levels of intensity: (1) imperceptible unless the operator is paying attention; (2) perceptible; and (3) no vibration. The stimulus provided to the fingers was to the thumb, index finger, and middle finger, and to one location in the palm. The following five combination patterns were prepared:

- (a) Fingers: Vibration (2) + Palm: Vibration (2)
- (b) Fingers: Vibration (2) + Palm: Vibration (1)
- (c) Fingers: Vibration (2) + Palm: Vibration (3)
- (d) Fingers: Vibration (1) + Palm: Vibration (2)
- (e) Fingers: Vibration (3) + Palm: Vibration (2)

Six research participants cooperated with the

experiment, each performing every pattern three times in random order for a total of 15 iterations. The participants were asked to describe whether the operating impression obtained in the various VR scissors environments was close to an actual operational feeling, rating the presence or absence of realistic sensation in seven levels.

As a result, the average values for operating impression placed the patterns in descending order as follows: (b)>(c)>(a)>(d)>(e). It was found from this that a lower intensity of tactile vibration feeling in the palm was preferred, and that having some tactile vibration feeling in the fingers that is not too strong was effective in producing an operating impression with a realistic sensation.

4.2. Relationship between Auditory Stimulus and Operating Impression

The next example to present here is the experiment to determine how cutting sounds, which are an auditory stimulus, affect the scissors operating impression. This experiment involved cutting in the VR system, described above, carried out under the no delay condition, which includes a 50 ms delay, and without any tactile vibration signal. The cutting sounds were not electronically synthesized sounds, but rather recordings of actual cutting sounds made using ordinary printer paper. The sounds were replayed to match the operation using VR scissors to cut VR paper. Seven types of recorded sounds that were envisioned with the use of everyday tools were prepared:

- (A) Blade length 45 mm, stainless steel, office use
- (B) Blade length 60 mm, stainless steel, office use
- (C) Blade length 75 mm, stainless steel, office use
- (D) Blade length 105 mm, stainless steel, office use
- (E) Blade length 140 mm, stainless steel, office use
- (F) Blade length 40 mm, stainless steel, zigzag scissors, office use
- (G) Blade length 100 mm, steel, sewing scissors, cloth use

Cutting sound (C) was used for the functional brain imaging described above as well as for sensory information delay tasks.

Six research participants were presented with three iterations of the experiment conditions in random order, for a total of 21 iterations. The participants were asked to evaluate their impressions of the sounds using seven levels to indicate the extent to which the sounds were close to actual operation sounds.

Results from comparison of the averaged impression evaluation scores showed that there was a descending order as follows: (A)(best)>(D)>(E)>(C)>(G)>(B)>(F) (worst). In addition, for example, comments from several of the research participants indicated that the cutting sound from (G) was a higher sound so that it felt lightweight in operation and did not feel real. Every cutting sound used in this experiment had its unique characteristics. From this existence of the evaluation order for the operating impression, it was found that there is an effective frequency band of cutting sounds for operating scissors, and that not

only the presence or absence of cutting sound but also the sound characteristics can change the operating impression. According to sensory evaluation for fatigue, the results showed that participants grew less tired in environments with a cutting sound⁽⁹⁾.

4.3. Relationship between Auditory-Tactile Stimulus and Operating Impression

From the sequence of research described above, the last experimental results⁽⁸⁾ to be introduced here will clarify how these auditory stimuli and tactile stimuli affect the operating impression. The experiment carried out with six research participants took place as follows. The VR experimental system was configured with condition (b) from Section 4.1 and condition (D) from Section 4.2 for the cutting sound conditions. The following four conditions were used in the comparative experiment.

- (1) CG only
- (2) CG with tactile stimulus
- (3) CG with auditory stimulus
- (4) CG with tactile stimulus and auditory stimulus

The research participants were asked to evaluate their impressions, responding with seven levels to indicate the extent to which the stimuli were close to actual operation stimuli. One point would be given when there was no realistic sensation, and seven points given when there was realistic sensation. Results from comparison of the averaged impression evaluation scores were (1) 2.3 points, (2) 3.8 points, (3) 5.3 points, and (4) 6.0 points. It was found from these results that the tactile stimulus raises the evaluation score in the VR paper cutting task using VR scissors, but that the effect is not as great as that achieved by auditory stimulus.

5. Handling and Stability of Driving as Viewed from Human factors

The paper to this point has described how sensory information and operating impression are related in connection with movement or activity. These findings will be summarized and examined in terms of the relationship between tools and human beings.

An abundance of sensorimotor system information accompanying operation is required, as explained in Chapter 2, in order to obtain the actual feeling of using a tool. Neural activity has a hierarchical structure. At the lower level that sends signals directly to the muscles, it is thought that before a muscle becomes active, it simulates the results of an activity program, or, in other words, it predicts its activity⁽¹⁰⁾. The activity simulation also simulates the sensory signals that are probably generated by activity. These simulations in the sensorimotor system compare the predictions with actual results of activity; that is, they compare to see whether the predictions match up with the physical world. Therefore, a sensory system has a predictive anticipation of input from the physical world for the kind of

sensorimotor activity that is going to be generated. In other words, the brain creates an information processing loop with respect to the control objective in order to ascertain the difference between the input and the prediction.

Meanwhile, activity programs, cognitive processes and other such activities of consciousness that have a cohesive unity are known to be retained for about three seconds at most, so that phenomena occurring within a period of three seconds are treated as a single psychological unit by the nervous system⁽¹¹⁾. There is also Pavlov's classical conditioning, and learning related to the stimulus is known to be reinforced by delayed conditioning as well as by simultaneous conditioning⁽¹²⁾. In other words, the central nervous system has a predisposition to automatically reinforce learning by the relationship between information input and motor output. Therefore, the operator's central nervous system works automatically to look for and form associations between work and information generated during work, and it learns the sensorimotor information processing loop.

Although termed learning, this is not some special cognitive activity. Any activity of the central nervous system simultaneously involves not only performance that achieves the work objective, but also learning that acquires knowledge and skills for the purpose of performing work tasks⁽¹³⁾. As described in Sections 4.1 and 4.2, simulated vibration and cutting sounds are presented as sensory feedback during VR scissors operation. That auditory-tactile VR information is presented at approximately the same time as the work task, and even though it is presented through the backs of the fingers and the palm of the hand, and from speakers, which makes it differ from the actual operation of scissors, this information is taken into the sensorimotor information processing loop and ends up being treated as real. This indicates how powerful learning is. Evaluation of the cerebral blood flow showed that the extent to which these sensations appear real was correlated with the abundance of sensory information input that is integrated with motor output. Therefore, the tool that is being operated becomes an extension of the operator's body, and in order to enhance that embodiment, or to maintain the embodiment, it is necessary to have sensory information of a quantity and quality appropriate to the work.

However, sensory information that is appropriate to the work does not simply mean sensory quantity. Chapter 3 led to the conclusion that time information must also be taken into account. When a time delay occurred in the presentation of sensory information, it was found to affect the magnitude of the operational load. A similar kind of phenomenon can occur during the operation of a personal computer when dragging an icon, but the response is delayed. This kind of phenomenon is described by the term "heavy" in Japanese (meaning sluggish), and it is referred to as pseudo haptic⁽¹⁴⁾. This suggests that when a driver evaluates a steering wheel as being "heavy," it is possible that the driver is not actually evaluating the steering

torque, but is rather experiencing what could be termed a kinesthetic illusion. When a driver operates an automobile, a time component is also incorporated into the sensorimotor system, so it is likely that the evaluation by a human being of handling and stability of driving must take time constant evaluation into account.

As noted earlier, sensory information appropriate to the work means information from the physical world relating to the control objective. Work in which the volume of information processing diminishes was found to have reduced cerebral blood flow in the area of activation. On the other hand, the absence of a cutting sound, meaning that there is no input of sensory information, invited a feeling of fatigue. These results mean that the information processing load in the brain and the feeling of fatigue or the sensation of load are not in a one-to-one correspondence. One of the brain's functions is to govern information processing, and it appears likely that when it is easier for the brain to create a sensorimotor loop that integrates action and sensory information so they are consistent, then that will contribute to the amelioration of fatigue.

The ultimate control objective in the operation of scissors is determined by whether the operator has been able to cut as desired. In the case of scissors, this is confirmed by the visual sense. It was found through the present experiments in a VR environment that the presentation of tactile and auditory information in addition to visual information, as described in Section 4.3, affects the feeling of engaging in actual operation. Information processing by the brain has a hierarchical structure, with conceptual levels placed higher and sensorimotor levels placed lower. The various hierarchical levels have their own separate control objectives for execution of the ultimate control objective of the highest order at those levels⁽⁴⁾. In other words, the system is structured so that execution of the information processing loop at each hierarchical level supports execution of the information processing loop of the highest order for the ultimate control objective. In the case of scissors, the ultimate control objective is to confirm the cutting trajectory. This is done by visual information, but additional auditory-tactile information is also important and affected evaluation of the feeling of having executed the ultimate control objective. The feeling of actual operation obtained by execution of the control objective at a lower level elicits more positive evaluation of the operation feeling of having executed the ultimate comprehensive control objective. It has also been reported, however, that in the case of a musical instrument, for example, a sensorimotor information processing loop for playing the instrument is also constructed⁽¹⁵⁾, but the control objective is the sound, which is auditory information. As this shows, the sensory information required for the operator to create a sensorimotor information processing loop differs with the tool. It is necessary, therefore, to clearly identify what sensory information is associated with physical information for evaluation of the handling and stability of driving in

the case of an automobile, and it is necessary to evaluate the extent to which information processing loops are constructed between the driver's operation oriented toward the control objective and the sensory information from that control objective.

The sensory information that is provided as feedback to receptors will be integrated as a rule when it has been generated in the same area as the motor output. However, although automobiles are operated using the hands and feet, the automobile behavior also constitutes sensory input to the driver's body in the form of acceleration or turning. For example, the feeling of accelerator pedal operation forms a sensorimotor information processing loop with the muscle activity in the foot and leg that pressed the pedal. When the operation simultaneously imparts movement to the automobile, movement by the automobile in five degrees of freedom also generates stimuli to the semicircular canals that are acceleration sensors in the driver's body, to the visual sense that detects optical flow, to the tactile sense and the pressure and pain sense in the driver's back when pressed against the seatback, to the somatic sense that grasps changes in the driver's body posture, and so on. Since this sensory information is generated simultaneously with movement, the nervous system by its nature will automatically create a sensorimotor information processing loop. In that sensorimotor information processing loop, sensory input that is created from changes in vehicle yaw, for example, may be felt with the driver's buttocks or hips, or sensed through the eyes, apparently depending on the individual. This input may also contain sensory illusions. The result in respect of formation of a loop to the ultimate control objective, however, is the same. What is important is that an information processing loop for sensory information that leads to an ultimate control objective is created at the same time that action is taken. Out of this variety of sensory information, only the information that can be associated with the action is selected and an information processing loop is created. It is due to the flexibility of the nervous system capable of doing this that people can switch from sedans to sports cars to trucks, and so on, all with different steering torque, steering wheel mounting angle, pedal force, and so on, and yet are still able to drive.

The above has demonstrated how important the perspective of sensorimotor information is in arriving at an evaluation of handling and stability of driving. When these factors are taken into consideration in thinking further about what we want automobiles to be, we find we must take care that measures against vibration and improvement of soundproofing performance not go too far. The driver's brain is always seeking the sensory information needed for movement and activity. That is to say, out of the variety of environmental information, it handles that information that is consistent with action as signal S, and it handles that information that cannot create an information processing loop as noise N. N cannot be generally defined as signals in the frequency band of so many kilohertz, and S as signals

in another. Suppose, for example, that a driver considers the 10 kHz band to be N in terms of evaluating drive comfort. The engineers pursue measures to block several decibels in the 10 kHz band. They take certain measures and then check the 10 kHz band for change. As this process repeats, the 10 kHz band represents the target for control by the engineers. The 10 kHz band is no longer N for these engineers but rather S, and even if it is buried inside another frequency band, that 10 kHz band is still an S representing soundproofing results. Information can be divided in this way into S and N according to the various information processing loops of different people, so vibration evaluation requires a perspective that takes into account what kind of information processing loop the driver will create when driving. A higher S/N ratio as well as the magnitude of S itself and time information are necessary to the operational feeling, but if S is vibration-proofed and sound-insulated to an excessive degree together with N, then the feeling of steering will become attenuated and the end result will be that the relationship between physical vehicle behavior and the driver becomes fragmented. This kind of vibration and sound are necessary as sensory information to generate an actual feeling that the driver is driving. Furthermore, these elements of sensory information change according to the physical environment while driving. Given considerations like these, it is conceivable that the handling and stability of driving is not simply about the capability of a vehicle, for example, to make a 0.2 G turn, but also involves an evaluation of time information processing of how physical information was acquired in conjunction with vehicle operation and how that process resulted in a 0.2 G turn.

6. Conclusion

The question of how making changes to the sensory information of a sensorimotor system in an experimental environment using VR technology affects the impression of using a tool was discussed in the course of introducing the results of preceding research on the subject. Given those various experimental results, the question of what it means to operate an automobile was examined in terms of neuroscience and psychology, and in doing so, an approach to establishing a method for evaluating the handling and stability of driving was found.

The aim for the future will be to clarify what physical phenomenon is the ultimate control objective for the driver in the vehicle movement that is achieved through steering, and what accompanying physical information is associated with that ultimate control objective. These can then contribute to the development of vehicles that enable more drivers to feel the vehicle behavior for themselves and operate the vehicle in ways that make it physically stable. A further aim is to examine the fun of driving as an emotion resulting from information processing, and to pursue its clarification. It is to be hoped that this paper will give impetus to the shift from evaluation of handling and

stability of driving in terms of tangible, hardware-related elements to evaluation in terms of intangible, software-related elements. Since this research has just begun, any opinions and suggestions will be welcome.

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