Advances in Social Sciences Research Journal – Vol. 12, No. 09
Publication Date: September 10, 2025
DOI:10.14738/assrj.1209.19351.

Sano, M. (2025). Quantitative Analysis of Hand-finger Movement During Musical Expression in Early Childhood: Focusing on the Movement of the First Metacarpal Bone. *Advances in Social Sciences Research Journal*, 12(09). 39-51.

SERVICES FOR SCIENCE AND EDUCATION

Quantitative Analysis of Hand-finger Movement During Musical Expression in Early Childhood: Focusing on the Movement of the First Metacarpal Bone

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ABSTRACT

In this study, finger movement in early childhood was quantitatively analyzed to clarify their characteristics in musical expression. The Meta gloves system, which captures finger movements in detail, was connected to the MVN system used for movement analysis, and 3-year-old, 4-year-old, and 5-year-old children in the three child facilities participated in the movement analysis of musical expression (n=86). A three-way non-repeated analysis of variance was conducted on the calculated data for 19 types of finger movements, and several characteristics were found in the metacarpal bone of the first finger. A three-way non-repeated ANOVA for the total moving distance, the moving average velocity, the moving average acceleration and the moving smoothness regarding the first metacarpal bone verified a contrast between the moving average acceleration and the moving smoothness. Regarding the moving average moving acceleration, in all of participant facilities, the data for bright melodies were faster than the dark melodies, and it was observed in a tendency for the participant children to show larger pretend movement of imagination in response to the bright melodies, and a tendency was apparent for the participant children to show larger active movement in response to the bright melodies. This tendency was particularly clear in the participant children in Y facility. It was also found that finger movements were more pronounced for brighter tunes. The moving smoothness was observed in not very fast but a steady rhythm, but it was found that the moving smoothness was significantly larger for the dark melody than the bright melody.

Keywords: Finger movement, The metacarpal bone of the first finger, Movement analysis, Meta gloves, A three-way analysis of variance.

INTRODUCTION

In order to capture the developmental process of musical expression in early childhood, the author has quantitatively captured changes in the elements of body movement through movement analysis during musical expression [1]. Using feature quantities extracted from the quantitative analysis results of the calculated data, machine learning with multiple classifiers has been implemented to examine classification discrimination [2]. Evaluation of developmental degree of music education at early stage is material for effective guidance to teach early childhood children. Existing methods of detecting developmental degree relied on observation by experts or communications / questionnaires with children. However, there was a great deal of ambiguity around evaluation because unexperienced teachers may overlook evolution of depictive music behavior or some of early childhood children may not be good at communicating with teachers. In order to overcome such weakness, the author introduced machine learning based evaluation platform. During the movement analysis, each participant child observes the surrounding children and the accompanying teachers and instantly decides the next action, so the author also focused on the gaze movement during musical expression and analyzed eye movement [3]. In 2022 and 2023, it was verified that eye movement could be an additional feature quantity to body movement through quantitative analysis based on the results of simultaneous analysis both body movement and eye movement during musical expression. As a result of machine learning, it was found that multiple classifiers, such as SVM and MLP-NN, showed improved classification accuracy when using feature quantities derived from the simultaneous analysis both body movement and eye movement rather than only body movement feature quantity [4].

If it were possible to present objective indicators that capture the developmental process of musical expression in early childhood by improving the discrimination accuracy regarding the developmental degree of musical expression, it would be significant to early childhood teachers who do not have much musical experience, in that they would be able to obtain information to consider the next musical experience to provide to each individual child. For this reason, the author tried to extract additional feature quantities.

In related fields, movement analysis focusing on hand movements has tended to capture a relationship between expert hand movements for a particular technique and eye movements accompanying hand movements. In education research, various motion capture systems (MCS) are gaining importance and are used for a variety of purposes and methods [5]. Research reports using 3D motion capture include the analysis of movements during dancing, specific skills, and walking, mainly for adults, and the development of learning support methods [6-11]. Some movement analysis of young children are observed in standing long jumps and ball throwing [12-13]. Research reports on music and movement show a reaction to sound and music, applications to piano teaching materials, video analysis of the relationship between a performer's movement and expression, and a suggestion for methods to evaluate the synchronization of hand movements and music [14-21].

Regarding movement analysis focusing on finger movements, the following researches have been observed: classification of hand movement functions [22]; analysis of finger movement coordination patterns and the synergistic effect of manipulation and gestures [23]; recommended toothbrush gripping methods when brushing teeth [24]; a method to model the range of movement of the human hand from joint angle data measured in various postures [25]; analysis of the tendon fixation action of the hand and fingers during typing [26]; analysis of upper limb and finger movements in putting and releasing movements [27]; educational use of motion capture systems for finger movements and data analysis of cooking movements [28-29]; quantitative analysis of catching movements in ball games and evaluation of grip strength of players' dominant and non-dominant hands [30-31].

In the field of music, examples of research include a relationship between the movements of the hands and upper body of pianists and their performance proficiency [32], analysis of the movements of the hands and fingers of expert pianists at fast tempos [33], upper limb movement control due to changes in volume when striking keys [34], hand movements when playing an instrument [35], changes in the coordination of the movement of the entire joints when playing the piano by expert pianists under psychological stress [36], obtaining movement parameters to support practice of instrument performance [20], and the impact of the movements of the hands, body, etc. of a conductor on the quality of music performance [37]. Regarding learning support, examples show an effect of gaze movement and finger use on learning [38], a quantitative analysis of 6-year-old children's finger movements in response to tasks [39], an examination of the effects of music on improving the learning of fine hand movements [40], and a method to evaluate the synchronization of hand movements and music [21]. Regarding the effect of musical training on the fine motor skills of elementary school children, eye-hand coordination, motor velocity and bimanual coordination have been measured [41]. Some researches investigated conditions that promote visual interaction during duet performances [42] and researches showing that factors such as musical characteristics affect the music-induced movements [43].

However, few studies have utilized motion capture to investigate musical expression in early childhood [1]. Notably, as young children frequently attempt to express their own imagery through hand and finger movements during musical expression [44], the author believes that is necessary for quantitative analysis specifically focused on these movements. Hands and fingers have complex structure with multiple joints and can perform wide range of tasks as well as vast amount of activities to figure out feelings and emotion. For example, finger-play is a part of music education field which has one of primary significance in musical expression. Therefore, observing all fingers dynamically at the same time by wearable devices could be fair candidates of additional feature quantity for improving forecasting accuracy of machine learning platform.

THE PURPOSE OF THIS STUDY

This study aims to quantitatively analyze of finger movements during musical expression in early childhood.

METHOD OF THIS STUDY

The following method shows the movement analysis and quantitative analysis of the hand and finger movements of early childhood children in musical expression. In this study, the MVN system (3D motion capture) was attached to the motion sensor only on the upper body, and the Meta gloves were attached to only one hand. This is because, based on the author's previous analysis and quantitative analysis results, characteristic calculation data was mostly acquired from the upper body in 2024.

The Movement Analysis of Finger Movement

In order to operate the Meta gloves, they must be connected to the MVN system. Each participant child put on both the MVN and the Meta gloves. Each child participated in the study one at a time, and since both systems had to be started, calibrated, and prepared each time, each measurement took 5 to 6 minutes. Next, the procedure for this movement analysis is shown.

Connection Between The MVN System and The Meta Gloves System:

Each child will participate in this movement analysis. The MVN system and the Meta gloves system will be started on one PC. The MVN system's motion sensors will be attached to 11 of the 17 designated measurement points on the upper body. The time frame is 1/60 seconds.

Wearing and Calibrating Meta Gloves:

Each child puts on the Meta gloves, a pair of gloves for early childhood children that the author created and equipped with sensors, and then the author turns them on. Calibration is conducted using three types of movements according to the display of the Meta glove system.

Figures 1-1 and 1-2 are photographs showing example children participating in measurements while wearing the MVN system (upper body) and Meta gloves.

Figure 1-1: A 4-year-old child wearing Meta gloves

Figure 1-2: A 4-year-old child wearing Meta gloves and participating in measurements

Calibration and Preparation of The MVN System:

The author will enter the necessary body information of each child according to the display of the MVN system, calibrate it, and each child will prepare for the measurement.

Analysis of Finger Movements in Musical Expression:

Each child performs body movement while singing nursery rhymes and finger-play songs, and the author analyzes and records the movements in real time.

Quantitative Analysis

In the movement analysis, data from 11 measurement points on the upper body and 19 points on the fingers are quantitatively analyzed. In particular, data from the following 19 points is required for finger movements: Thumb (1st metacarpal, 1st proximal phalange, 1st distal phalange), index finger (2nd metacarpal, 2nd proximal phalange, 2nd middle phalange, 2nd distal phalange), middle finger (3rd metacarpal, 3rd proximal phalange, 3rd middle phalange, 3rd distal phalange), ring finger (4th metacarpal, 4th proximal phalange, 4th middle phalange, 4th distal phalange), and little finger (5th metacarpal, 5th proximal phalange, 5th middle phalange, 5th distal phalange). Next, the total moving distance, the moving average velocity, the moving average acceleration, and the moving smoothness were calculated for the processing data for each part, and a quantitative analysis was conducted mainly on a three-way non-repeated analysis of variance with the factor of early childhood facility (3 levels), tune factor (2 levels), and age factor (3 levels) to investigate whether any statistically significant difference was observed or not in the average data. In this study, the tunes are divided into light and dark, with songs in major keys being shown as "bright, and traditional Japanese nursery rhymes and songs in minor keys being shown as "dark".

Measurement Dates, Participant Facilities in Early Childhood and Number of Participants

The measurement dates, participant facilities in early childhood and number of participants for 2024 are as shown in Table 1 below.

Table 1: Schedule, participant facilities, and number of participants for the hand and finger movement analysis in 2024

	T facility (n=29)	W facility (n=28)	Y facility (n=29)
date	June 4th 14:05～15:05 June 11th 15:20～16:20	July 2nd 15:20～16:25 July 5th 15:20～16:10	September 13th 12:30～14:40
song	Higejiisan Guchokipadenanitsukurou	Tokeinouta Genkotsuyamanotanuki	Kaerunouta Usagi
date	June 18th 14:10～14:55 June 25th 14:15～15:00	July 9th 15:20～16:20 July 12th 15:20～16:20	September 27th 12:00～14:30
song	Panyasanniokaimono Agarimesagarime	Panyasanniokaimono Agarimesagarime	Yamanoonngakuka Hotarukoi
date	June 25th 15:30～16:05 June 28th 14:15～16:30	July 23th 15:20～16:45 July 24th 15:30～16:15	
song	Yamanoonngakuka Nabenabesokonuke	Yamanoonngakuka Nabenabesokonuke	
number	3-year-old: 10 4-year-old: 10 5-year-old: 9	3-year-old: 7 4-year-old: 10 5-year-old: 11	3-year-old: 8 4-year-old: 10 5-year-old: 11

RESULTS

Among the many types of data acquired from this measurement, the metacarpal part of each finger is most relevant to the movement of the fingers while singing. Therefore, the author focuses on the results of a quantitative analysis of the total moving distance, the moving average velocity, the moving average acceleration, and the moving smoothness of the first metacarpal part, which corresponds to the thumb, which is fundamental when expressing the recognition of image movement and rhythm, and present its characteristics.

The Moving Distance and the Moving Trace of the Right-hand Fingers

The following Figure 2-1 shows an example of the moving distance of 19 types of finger calculation data for a 3-year-old child who expressed by body movement while singing "Tontontonhigejisan" in T facility. In Figure 2-1, the 19 types of calculated data listed in Method 3.2 of the aforementioned study are numbered 1 to 19. Among them, number 1 corresponds to the moving distance of the thumb (first metacarpal bone), which has a relatively large moving distance and is the basis for supporting the movements of the other measured parts of the fingers. Figure 2-2 shows an example of the moving trace of the thumb (first metacarpal bone) for an example of the same 3-year-old child.

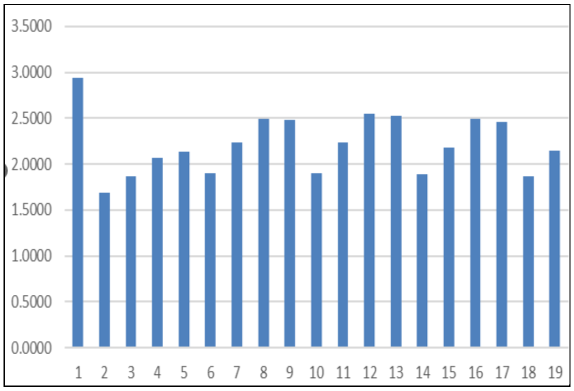

Fig 2-1: Example of the moving distance calculated for 19 types of fingers (m).

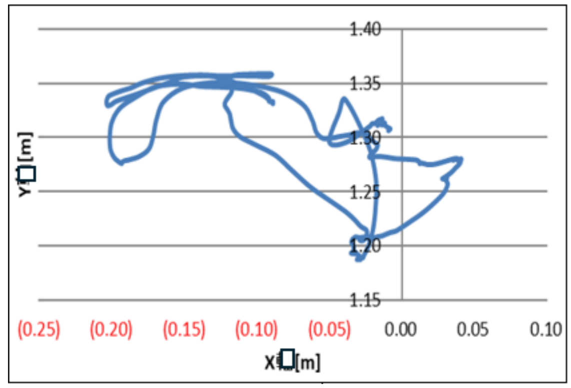

Fig 2-2: Example of the moving trace of thumb (first metacarpal bone)

The Moving Distance of the Thumb (First Metacarpal Bone)

The following table 2 shows the moving average distance of the first metacarpal bone of the thumb by facility and age.

Table 2: The moving distance of the first metacarpal bone (m)

Facility	Tunes	Age	Mean	SD	N
		3-year-old	3.9089	1.7275	37
T facility	bright	4-year-old	4.7404	2.3253	37
		5-year-old	5.3499	1.9146	33
		3-year-old	2.2601	1.3908	17
	dark	4-year-old	1.9017	1.4031	20
		5-year-old	3.9311	3.2366	18
		3-year-old	4.6315	2.7117	18
W facility	bright	4-year-old	3.9329	1.4639	29
		5-year-old	5.1011	2.9655	31
		3-year-old	1.9677	1.3959	18
	dark	4-year-old	2.0556	1.6088	29
		5-year-old	3.2441	2.2849	31
		3-year-old	6.8858	3.1060	16
Y facility	bright	4-year-old	7.9691	3.9039	15
		5-year-old	8.5662	3.1681	20
		3-year-old	3.4450	1.8536	16
	dark	4-year-old	3.8423	1.9945	15
		5-year-old	4.638208	1.4113	20

Those data were quantitatively analyzed by a three-way ANOVA (non-repeated factors as 3 levels in T child facility, W child facility, Y child facility, non-repeated factors as 2 levels in the melody (bright)/ melody (dark), non-repeated factors as 3 levels in 3-year-old, 4-year-old, 5-year-old). Regarding those acquired data, the melody (bright) means a song in major key, and the melody (dark) means a song in minor key or Japanese traditional song such as "Warabeuta". As a result of a three-way ANOVA for these acquired data of the moving distance by the first metacarpal bone, the average values of which are shown in Table 1, a main effect / interaction between subjects of the test showed a statistically significant difference (melody: ($F(1, 402)=129.119$, $p<.05$), age: ($F(2, 402)=12.226$, $p<.05$), melody * facility: ($F(2, 402)=5.797$,

p<.05)). Concerning the facility factor/ facility * melody * age, the simple main effect was significant in melody (bright) (3-year-old: $F(2, 402)=9.649$, $p<.05$), 4-year-old: $F(2, 402)=16.264$, $p<.05$), 5-year-old: $F(2, 402)=16.565$, $p<.05$) and melody (dark) (4-year-old: $F(2, 402)=3.840$, $p<.05$). As a result of multiple comparison test, the average data in W facility was larger for 3-, 4-, and 5-year-olds in the melody (bright), and larger for 4-year-old in the melody (dark).

Concerning the melody factor/ facility * melody * age, the simple main effect was statistically significant in T facility((3-year-old: $F(1, 402)=6.147$, $p<.05$), 4-year-old: $F(1, 402)=20.310$, $p<.05$), 5-year-old: $F(1, 402)=4.551$, $p<.05$)), W facility ((3-year-old: $F(1, 402)=12.398$, $p<.05$), 4-year-old: $F(1, 402)=9.921$, $p<.05$), 5-year-old: $F(1, 402)=10.377$, $p<.05$)), and Y facility ((3-year-old: $F(1, 402)=18.387$, $p<.05$), 4-year-old: $F(1, 402)=24.798$, $p<.05$), 5-year-old: $F(1, 402)=29.953$, $p<.05$)). A result of multiple comparison test showed that the data in the melody (bright) was significantly larger than the melody (dark) for 3-, 4-, and 5-year-old in T, W, and Y facilities.

Concerning age factor/ facility * melody * age, the simple main effect was statistically significant in T facility (melody (bright): $F(2, 402)=3.570$, $p<.05$), melody (dark): $F(2, 402)=4.202$, $p<.05$). As a result of multiple comparison test, the data of 5-year-old was significantly larger than 3-year-old in the melody (bright) in T facility, and the data of 5-year-old was significantly larger than 4-year-old in the melody (dark).

Figures 3-1 and 3-2 show the changes in the moving distance by the first metacarpal bone of the thumb by participant children at three child facilities in 2024 depending on the age of the child when the melody was bright or dark.

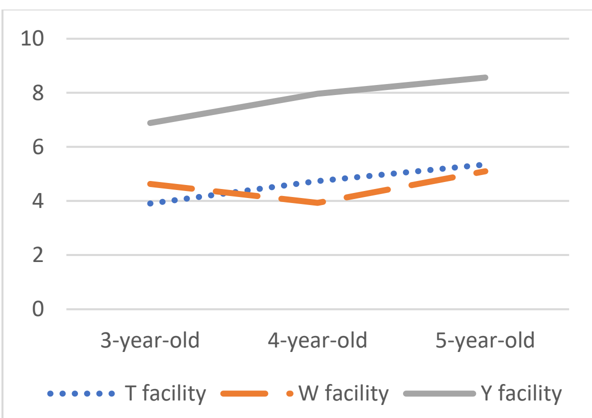

Figure 3-1: thumb (first metacarpal): The moving distance (m) for the melody (dark) in the three facilities.

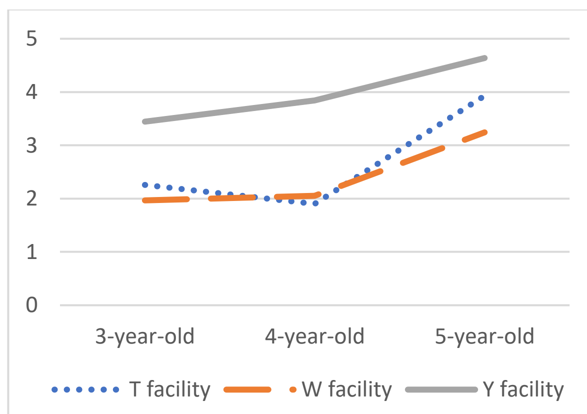

Figure 3-2: thumb (first metacarpal): The moving distance (m) for the melody (bright) in the three facilities.

As shown in Figures 3-1 and 3-2, the moving distance was significantly larger for the melody (bright) than for the melody (dark), and although some differences were observed depending on the facilities, 5-year-old tended to show a larger distance than 3-year-old. In addition, it was found that the average data in Y facility was significantly larger for the facilities.

The Moving Average Velocity of the First Metacarpal Bone

As a result of a three-way ANOVA in the same way as for the moving distance, a main effect/ interaction between-subject of the test showed a statistically significant difference in the facility factor ($F(2, 402)=11.227$, $p<.05$), melody factor ($F(1, 402)=8.122$, $p<.05$), age factor ($F(2, 402)=15.392$, $p<.05$), and facility * melody factor ($F(2, 402)=21.754$, $p<.05$). A simple main effect for the facility factor was statistically significant for the melody (bright) for 3-year-old ($F(2, 402)=9.176$, $p<.05$), 4-year-old ($F(2, 402)=9.692$, $p<.05$), and 5-year-old ($F(2, 402)=11.376$, $p<.05$), and for the melody (dark) regarding 4-year-old ($F(2, 402)=5.488$, $p<.05$). Aa a result of multiple comparison test, Y facility was significantly larger than T and W facility for 3-, 4-, and 5-year-olds in the melody (bright), and T facility was significantly larger than Y facility regarding 5-year-olds in the melody (dark).

Concerning the tune factor/ facility* melody* age, the simple main effect was statistically significant for 5-year-old in T facility: ($F(1, 402)=12.168$, $p<.05$), 3-year-old in Y facility: ($F(1, 402)=13.823$, $p<.05$), 4-year-old in Y facility: ($F(1, 402)=12.230$, $p<.05$), and 5-year-old in Y facility: ($F(1, 402)=15.668$, $p<.05$). As a result of multiple comparison test, the melody (dark) was significantly larger than the melody (bright) regarding 5-year-old in T facility, and the melody (bright) was significantly larger than the melody (dark) regarding 3-, 4-, and 5-year-old in Y facility.

Concerning the age factor/ facility* melody* age, the simple main effect was statistically significant in the melody (dark) (Y facility: ($F(2, 402)=9.738$, $p<.05$), W facility: ($F(1, 402)=6.558$, $p<.05$)). As a result of multiple comparison test, 5-year-old was significantly larger than 3- and 4-year-olds in the melody (dark) in T facility, and 5-year-old was significantly larger than 3- and 4-year-olds regarding the melody (dark) in W facility. Although a statistically significant difference was observed in the moving average velocity depending on the melody in T and W facility, it was shown that participant children represent the recognition of regular beats and rhythms. 5-year-old children showed significantly larger data than 3-year-old children, and it was also shown that the recognition of musical elements such as beats and rhythms was progressing with age. The moving average velocity in Y facility was significantly faster for the melody (bright) than the melody (dark), and more active movements were observed.

The Moving Average Acceleration of the First Metacarpal Bone

As a result of three-way ANOVA in the same way as for the moving distance, a main effect/ interaction between-subject of the test showed a statistically significant difference in the facility factor ($F(2, 402)=5.221$, $p<.05$), the melody factor ($F(1, 402)=33.248$, $p<.05$), and the facility * melody factor ($F(2, 402)=9.113$, $p<.05$).

Concerning the facility factor/ facility * melody * age, the simple main effect was statistically significant in the melody (bright) (3-year-old: ($F(2, 402)=4.242$, $p<.05$), 4-year-old: ($F(2, 402)=4.187$, $p<.05$), 5-year-old: ($F(2, 402)=6.929$, $p<.05$). As a test of multiple comparison test showed that for the melody (bright) the data in Y facility was significantly larger than in T facility regarding 3-year-old, and the data in Y facility was significantly larger than T and W facility regarding 4- and 5-year-old.

Concerning the melody factor/ facility * melody * age, the simple main effect was statistically significant for 4-year-old in T facility ($F(1, 402)=3.991$, $p<.05$), 5-year-old in W facility ($F(1, 402)=4.721$, $p<.05$), and 3-year-old in Y facility ($F(1, 402)=7.381$, $p<.05$), 4-year-old ($F(1, 402)=12.134$, $p<.05$), and 5-year-old ($F(1, 402)=21.462$, $p<.05$). As a result of multiple comparison test, the data of melody (bright) was significantly larger than the melody (dark) for 4-year-old in T facility, the data of melody (bright) was significantly larger than the melody (dark) for 5-year-old in W facility, and the data of melody (bright) was significantly larger than the melody (dark) regarding 3-, 4-, and 5-year-old in Y facility. Concerning the age factor/ facility* melody* age, the simple main effect was statistically significant for the melody (bright) in W facility ($F(2, 402)=3.161$, $p<.05$). As a result of multiple comparison test, 5-year-old were more sensitive than 4-year-old regarding the melody (dark) in T facility.

For each participant child, the moving average acceleration was significantly larger for the melody (bright) than the melody (dark), and the children tended to show larger pretend movements by imagination in response to the melody (bright), which was evident in Y facility.

The Moving Smoothness of the First Metacarpal Bone

As a result of three-way ANOVA in the same way as for the moving distance, a main effect/ interaction between-subject of the test was statistically significant in the melody factor ($F(1, 402)=56.933$, $p<.05$) and the facility * melody factor ($F(2, 402)=4.941$, $p<.05$).

Concerning the facility factor, the simple main effect was statistically significant for the melody (dark) regarding 4-year-old ($F(1, 402)=4.839$, $p<.05$) and 5-year-old ($F(1, 402)=3.319$, $p<.05$). As a result of multiple comparison test showed that the data for the melody (dark) regarding 4-year-old was significantly larger in Y facility than W facility.

Concerning the melody factor, the main effect was statistically significant (T facility (4-year-old: ($F(1, 402)=13.099$, $p<.05$), W facility (4-year-old: $F(1, 402)=6.264$, $p<.05$), 5-year-old: $F(1, 402)=17.550$, $p<.05$), Y facility (3-year-old: $F(1, 402)=7.267$, $p<.05$), 4-year-old: $F(1, 402)=19.280$, $p<.05$), 5-year-old: $F(1, 402)=9.133$, $p<.05$)). As a result of multiple comparison test, the data for the melody (dark) was significantly larger than the melody (bright) regarding 4-year-old in T facility, The data for the melody (dark) was significantly larger than the melody (bright) regarding 4- and 5-year-old in W facility, and the data for the melody (dark) was significantly larger than the melody (bright) regarding 3-, 4-, and 5-year-old in Y facility.

Concerning the age factor, the main effect was statistically significant for the melody (dark) in T facility ($F(2, 402)=4.635$, $p<.05$). A result of multiple comparison test showed that the data for the melody (dark) was significantly in T facility regarding 4-year-old than for 5-year-old.
For the melody (dark), the participant children tended to show larger moving smoothness than the melody (bright), and slower, pulsating movements were observed in response to the melody (dark) in Y facility.

DISCUSSION

In this study, the author showed a result of quantitative analysis focusing on the calculated data regarding the first metacarpal bone of the thumb, where the moving distance was particularly large, as shown in Figure 1, for the finger movements during musical expression was analyzed in 2024.

As a result of three-way non-repeated analysis of variance, a statistically significant difference was observed in the average data for the factors of melody, facility, and age, with the difference due to the melody being particularly notable. The moving distance was significantly larger for the melody (bright) than the melody (dark), and this tendency was observed in all three facilities, with the tendency being more clearly evident in Y facility. Regarding the moving average velocity, it was observed in a tendency to recognize regular rhythm in both bright and dark melodies, and rather than an increase with age, it could be interpreted as a deepening of awareness of rhythm as a musical element. Regarding the moving average moving acceleration, in all of participant facilities, the data for the melody (bright) were faster than the melody (dark), and it was observed in a tendency for the participant children to show larger pretend movement of imagination in response to the melody (bright), and a tendency was apparent for the participant children to show larger active movement in response to the melody (bright). This tendency was particularly clear in the participant children in Y facility.

On the other hand, the moving smoothness was observed in not very fast but a steady rhythm, but it was found that in all the participant facilities, the moving smoothness was significantly larger for the melody (dark) than the melody (bright). This characteristic was in contrast to the characteristic that the thumb movement, which tried to express the participant child's image of the song in the bright melody, was greatly reflected in the moving average acceleration.

CONCLUSION

This study verified that the characteristics of the first metacarpal movement were that the pretend movement by imagination became more active in response to a bright melody, and that the pretend movement by imagination slowed down in response to a dark melody, while a steady beat of movement became more apparent. In this way, it was found that the children in this study were able to evoke images through lyrics that elicit body movement, but that they were more likely to respond to bright melodies and actively express images with their fingers. In my future task, as to increase the amount of measurement data, it will be necessary to clarify characteristics of finger movements that were not shown in this article.

ACKNOWLEDGEMENT

This study was supported by Grant-in-Aid for Scientific Research (C) 24K05845.

ETHICAL CONSIDERATIONS

This study was reviewed and approved by the research ethics committee of the affiliation of the author, and informed consent was obtained through the submission of consent forms by the cooperating facilities, the parents of the participant children, and the person in charge of the participant facilities.

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