Vibrotactile and Force Collaboration within 3D Virtual Environments

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***Abstract*— In a three-dimensional (3D) virtual environment (VE), proper collaboration between vibrotactile and force cues – two cues of the haptic modality – is important to facilitate task performance of human users. Many studies report that collaborations between multi-sensory cues follow maximum likelihood estimation (MLE). However, an existing work finds that MLE yields a mean and an amplitude mismatches when interpreting the collaboration between the vibrotactile and force cues. We thus proposed mean-shifted MLE and conducted a human study to investigate the mismatches. For the study, we created a VE to replicate the visual scene, the 3D interactive task, and the cues from the existing work. Our participants were biased to rely on the vibrotactile cue for their tasks, departing from unbiased reliance on both cues in the existing work. Assessments of task completion time and task accuracy validated the replication. We found that based on task accuracy MLE explained the cue collaboration to certain degrees, agreed with the existing work. Mean-shifted MLE remedied the mean mismatch, but maintained the amplitude mismatch. Further examinations revealed that the collaboration between both cues may not be entirely additive. This sheds an insight for proper modeling of the collaboration between the vibrotactile and force cues to aid interactive tasks in VEs.**

***Keywords*— Cue collaboration, MLE, mean-shifted MLE, VEs**

I. Introduction

Information and feedback of the visual modality can be overwhelming to the human user of a three-dimensional (3D) virtual environment (VE) [1]. Increasingly, the VE incorporates feedback of other modalities such as haptics and auditory to provide the user both a sense of presence and interactivity [1]–[3]. Feedback of the haptic modality is especially important, because this modality corresponds to direct touching an object for interaction. Such touch allows for an interactive experience in the VE to promote a greater sense of presence for the user and, thereby, to enhance user performance [1]. In the haptic modality, two commonly used types of feedback are through vibrotactile and force cues. This arises from both availability and relative ease of acquiring devices, which can delivers these haptic cues.

Vibrotactile and force cues are often delivered to the user collaboratively in either a co-located or dis-located setting. When interacting with an object in the real world, the user expects feedback directly co-located with the object [4]. However, co-located cues may be difficult to deliver in the VE due to restrictions in the design and implementation of haptic devices [4]. In cases where co-located cues are infeasible, dis-located cues can be delivered to the user instead. While the co-located cues have shown to offer better user performance than dis-located cues [5], the dis-located cues nevertheless are a means of improving user performance in the VE [6]. A general mechanism of collaboration between vibrotactile and force cues would be necessary to facilitate the user performance.

One potential candidate of the mechanism is maximum likelihood estimation (MLE) [2], [7], albeit the existence of information integration theory and signal detection theory [8]. In brief, MLE yields a predicted Gaussian distribution of a cue collaboration based on empirical observations of individual cues [2], [7]. The characteristic parameters of the prediction are its mean (μ), standard deviation (σ), and amplitude (A). Based on these parameters, MLE elucidates herein the cue collaboration when the prediction matches its empirical observation. Most existing reports reveal that MLE indeed explains appropriately cue collaborations between visual and haptic cues [2], force and position cues [9], as well as auditory and visual cues [10].

In contrast, this explanation is inconclusive when applying MLE to interpret empirical observations of collaboration between vibrotactile and force cues [11]. In the co-located setting of the cues, MLE elucidates the cue collaboration at certain degrees through a mean match between a prediction and an empirical observation. The same match eludes surprisingly in a dis-located setting of the cues, leading to a mean mismatch. Moreover, an amplitude mismatch exists between the prediction and the observation in both settings. The inconclusiveness derived from these mismatches warrants further investigations.

Little work has been done to investigate these mismatches, hence we conducted an empirical study, in which each human participant undertook a 3D interactive task within a VE. We created the VE to replicate the visual scene, the task and the cues from those in the existing work [11]. Departing from a unbiased reliance on either of the cues in the existing work [11], each participant in the current study was instructed to favor the vibrotactile cue over the force cue. In other words, the participant had a biased reliance on the vibrotactile cue. Although assessments of task completion time and task accuracy for all participants validated the replication, we found the same mismatches when applying MLE to explain the cue collaboration. The mean mismatch was interpretable nevertheless using our proposed mean-shifted MLE that linked the weights of the individual cues to the means of their observations. Based on our reliance-biased observations and the reliance-unbiased observations from the existing work, further examinations yielded a linear relationship between the

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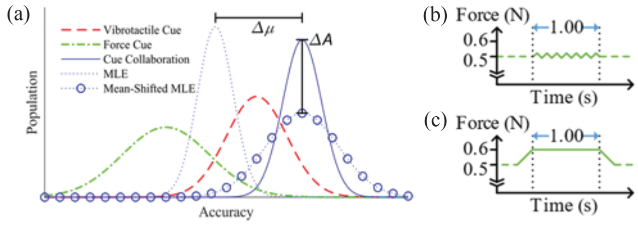

Fig. 1. Collaboration and cues: (a) concepts of MLE and mean-shifted MLE on a cue collaboration; (b) a vibrotactile cue; and (c) a force cue.

amplitude difference and the difference of the mean-shifted weights. This gives an insight for proper modelling of the cue collaboration, as future work, to aid interactive tasks in VEs.

II. MLE and Mean-Shifted MLE

In MLE, the prediction ($\hat{S}$) of a collaboration among N individual cues is estimated by summing the weighted empirical observations ($\hat{S}_i,\ i \in \{1,..,N\}$) of the cues as follows [2]:

$$\hat{S} = \sum_{i=1}^{N} W_i \hat{S}_i, \tag{1}$$

where the weight ($W_i = \frac{1/\sigma_i^2}{\sum_{j=1}^{N} 1/\sigma_j^2}$) of the i-th cue's observation is related to its standard deviation (σ_i), given that each observation is a Gaussian distribution. Thus, the prediction ($\hat{S}$) yielded by Eq. (1) is also a Gaussian distribution.

Notwithstanding, what modifications of MLE are needed to remedy the two mismatches found in the existing work [11]? For handling the mean mismatch, we proposed mean-shifted MLE. Departing from a MLE weight W_i, the weights of individual cues in mean-shifted MLE are derived by using the means of the observations of the cues and their collaboration. Considering the vibrotactile and force cues (as $N = 2$), their mean-shifted weights (W_V and W_F, respectively, for W_1 and W_2) have then the following formulations as:

$$W_V = \frac{\mu_F - \mu_{FV}}{\mu_F - \mu_V} \quad \text{and} \quad W_F = \frac{\mu_{FV} - \mu_V}{\mu_F - \mu_V}\ , \tag{2}$$

where μ_V, μ_F, and μ_{FV} represent the means of the observations of the vibrotactile cue, the force cue and their cue collaboration, respectively. In essence, the mean-shifted weights of the cues are what their MLE weights would be to ensure a mean match between the prediction and the observation of the cue collaboration. The prediction is the sum of the weighted observations of the cues as defined in Eq. (1), but with their mean-shifted weights as formulated in Eq. (2).

To interpret the amplitude mismatch, we defined the difference of the amplitudes (ΔA) between the prediction and observation of the cue collaboration as:

$$\Delta A = A_{emp} - A_{pred}\ , \tag{3}$$

where A_{pred} and A_{emp} are the amplitudes of the prediction and the observation of the cue collaboration, respectively. We noted the amplitude difference (ΔA) as a function (f) of the difference between the mean-shifted weights as below:

$$\Delta A = f(W_V,\ W_F)\ . \tag{4}$$

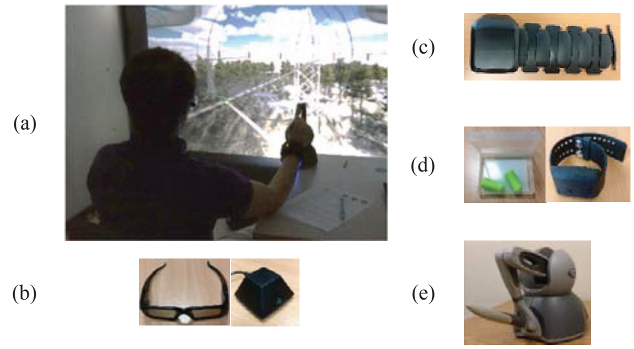

Fig. 2. A VE and devices utilized for user interaction: (a) the VE and its layout; (b) 3D shutter glasses and IR emitter; (c) VibroTac bracelet; (d) ear plugs and an E4 wristband; and (e) Omni device.

Examinations based on the observations warrant to refine Eq. (4) as a relationship between ΔA and the mean-sifted weights.

Figure 1 shows the concepts of MLE and mean-shifted MLE, and illustrates the vibrotactile and force cues. A mean shift ($\Delta\mu$) represents the mean difference between the MLE and mean-shifted MLE predictions, while the amplitude difference (ΔA) is defined in Eq. (3). Thus, mean-shifted MLE provides a mechanism to examine the collaboration between the vibrotactile and force cues.

III. Empirical Study

We conducted an empirical study to verify the applicability of mean-shifted MLE. For this study, we developed a 3D stereoscopic VE for human participants to undertake an interactive task. The visual scene, interactive task and cues of the VE replicated their originals in the existing work [11]. Comparable hardware were used to deliver similar interactive experience to the participants who were biased to favor the vibrotactile cue over the force cue for the interactive task.

A. Virtual Environment

In brief, the VE was created using Unity 3D game engine (version 5.3.4f). All visual and haptic components of the VE were managed using the C# language. Figure 2 depicts the VE and devices utilized for user interaction. As shown in Fig. 2(a), the stereoscopic visual scene of the VE was projected on a screen (2.4×2.4 m^2) using an Acer U5200 projector (Acer Inc., Taiwan) operated at 120 Hz. A pair of 3D shutter glasses and an IR emitter (nVidia Inc., Santa Clara, USA), as depicted in Fig. 2(b), allowed each participant to view the scene. A VibroTac bracelet (SENSODRIVE Gmbh, Germany) presented in Fig. 2(c) delivered a vibrotactile cue to the right hand or the forearm of the participant. As depicted in 2(d), a pair of ear plugs were used to block out the noise generated by the VibroTac bracelet when delivering the vibrotactile cue. The participant wore an E4 wristband (Empatica Inc., Italy) on his/her left wrist to monitor physiological signals in real time. A PHANToM Omni device (Geomagic Inc., USA), as shown in Fig. 2(e), inputted interactive commands and provided the force cue to the participant's right hand. Two Unity 5 plugins were applied to activate the VibroTac bracelet and the Omni device. A vibrotactile plugin was made by the Art et Métiers, France; and a force plugin was provided by the Digital Design Studio at the Glasgow School of Art, United Kingdom.

As illustrated in Fig. 2(a), each participant sit on a chair and employed his/her right hand to hold the Omni device on a small table for 3D interaction. The chair was positioned at a distance of 2.0 m from the center of the screen. The right elbow of the participant was rested on the small table. The visual scene of the VE consisted of a high-powered transmission line in a mountainous region. The transmission line was supported by two towers and curved towards the ground due to its own weight. The supporting towers were 60.00 m apart. The participant was required to fly and guide a drone along the transmission line with the Omni device. A stereo camera was attached to the front of the drone and served as the viewport of the participant. Attached to the bottom of the drone was a robotic arm, at which end there was a loop-shaped clamp. The clamp covered the transmission line for detecting defects on the line. The defects were indiscernible visually from the rest of the transmission line. Through the VibroTac bracelet and/or the Omni device, the defects were delivered as vibrotactile and/or force cues to the participant, respectively.

The VE was run on a Dell Precision WorkStation T3500 (Dell Inc., USA) under the Microsoft Windows® 7 operating system with an Intel Xeon E5507 CPU, an nVidia Quadro FX4800 graphics card, and 8GB of RAM.

B. Participants

Ten participants (mean age of 27.13 ± 5.13 years old) took part in the study. Being naïve to the purpose of the study, all participants differed from those of the existing work [11]. A pre-assessment consisted of an Edinburgh handedness test, an Ishihara color-blindness test, and a Randot stereo test. The assessment indicated that each participant was right-handed with regular color vision, and had normal or corrected-to-normal vision with stereo acuity of at least 40" of arc. An ethics approval was attained at our institute for the study.

C. Procedure

The procedure in this study was largely identical to that in the existing work [11], but with one exception. Departing from an unbiased reliance on both vibrotactile and force cues in the existing work, the expectation was a biased reliance on the vibrotactile cue instructed to each participant.

In brief, the interactive task for each participant was to inspect and detect the defects on the curved transmission line using the robotic arm on the flying drone. To move the drone, the participant had to point the stylus tip of the Omni device along the transmission line while pressing the dark-gray button on the stylus. While flying, the clamp of the robotic arm covered the transmission line for sensing its surface. To guide the participant along the line, the Omni delivered a 0.50 N continuous force tangentially to the line.

Additional vibrotactile and/or force cues, as shown in Figs. 1(b) and 1(c), were delivered to the right hand (and/or forearm) of each participant when any defect existed on the transmission line. The vibrotactile cues were provided by the first motor of the VibroTac bracelet in one of two settings: co-located with the Omni device on the right hand or dis-located from the device on the right forearm. The vibration was 1.00 s long at a frequency of about 200 Hz and superimposed on the continuous force. The motor was placed on the skin covering the first dorsal interosseous muscle between the thumb and the index finger in the co-located setting; and at the carpi radialis longus muscle of the forearm in the dis-located setting. Delivered through the stylus of the Omni device to the right hand, the force cues was 0.60 N (i.e., 0.10 N increment on the top of the continuous force) and lasted 1.00 s excluding the pre- and after-ramping of 0.25 s.

While moving the clamp along the transmission line, each participant declared his/her detection of a defect by pressing down both buttons on the stylus of the Omni device. There were 5 cue profiles, with a profile being one testing block, as follows:

- V_co: The cue signaled a defect was only a vibrotactile cue co-located with the Omni stylus.
- V_dis: The cue signaled a defect was only a vibrotactile cue dis-located from the Omni stylus at the forearm.
- F_only: The cue signaled a defect was only a force cue delivered by the Omni stylus.
- FV_co: The cue signaled a defect consisted of the vibrotactile cue of the V_co profile in the co-located setting with the force cue of the F_only profile.
- FV_dis: The cue signaled a defect consisted of the vibrotactile cue of the V_dis profile in the dis-located setting with the force cue of the F_only profile.

The cues and cue profiles were detailed in the existing work [11]. Prior to each testing block, there was a practice block for the participant to learn how to fly the drone and detect defects. After each block, the participant answered one cybersickness [12] and one perceptual questionnaires [11]. The Empatica wristband was worm by the participant on the left wrist from the pre-assessment to the end of all blocks.

The length of the procedure, including the pre-assessment and a 2-minute break between any two blocks, lasted about 1.75 hours for each participant. The order of the testing blocks were counter-balanced among all participants.

D. Data Collection and Analyses

The steps of data collection and analyses were similar in this study and the existing work [11], except the addition of mean-shifted MLE to the analyses in the last step.

Briefly, both objective and subjective data were collected in the first step during each testing block. Objective data were logged by the Emptica wristband to monitor each participant's physiological signals for cybersickness; and by the VE to yield the participant's performance, including task completion time and task accuracy of detecting defects. Subjective data was gathered using the cybersickness and perceptual questionnaires. The later covered the components of perceived usefulness, effectiveness, pleasure and workload of the VE. The first three components were constructed using a variation of the Likert scale, which had a continuous bar bounded between 0% and 100%. For consistency, each question related directly to the participant's actions [13]. The last component utilized the NASA task load index (TLX) [14]. All subjective data, except cybersickness ones, were converted to numeric for comparison.

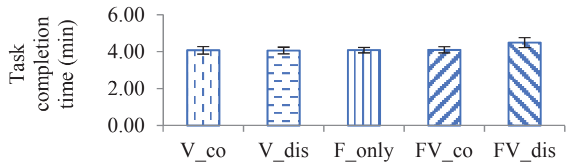

Fig. 3. Average task completion time. [Error bars are standard errors.]

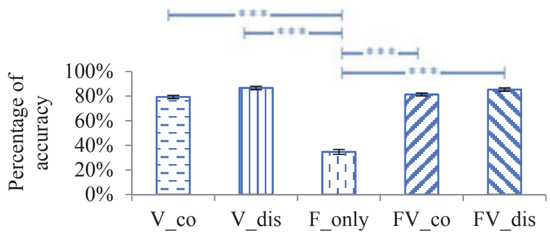

Fig. 4. Average accuracy in detecting the defects on the transmission line. [Error bars represent standard errors. The symbol of *** denotes Bonferroni significant differences with $p < 0.001$.]

In the second step, cybersickness was assessed using both the physiological signals recorded by the wristband and the responses gathered from the cybersickness questionnaire. Should a participant suffer from cybersickness, his/her data was excluded from analyses.

To validate our replication and determine the baseline for using MLE, other objective and subjective data were compared in the third step using one-way repeated-measure analyses of variance (ANOVA) [15]. Any significant difference was evaluated further through a Bonferroni post hoc test [15]. Data eligibility for ANOVA analyses was determined by using Anderson-Darling normality tests [16].

In the last step, both MLE described in Eq. (1) and mean-shifted MLE were applied to the same data. The mean-shifted weights, W_V and W_F, were calculated from Eq. (2) for the individual vibrotactile and force cues, respectively. The weights were then used to compute the prediction of the collaboration between the vibrotactile and force cues. All analyses of this step were based on task accuracy in this study and the existing work.

IV. Results

None of the participants suffered from cybersickness. This was confirmed by the physiological data and the responses to the cybersickness questionnaire. Thus, the data of all participants were used in the analyses.

Normality tests on other objective and subjective data showed that all the data were normally distributed and therefore eligible for ANOVA analyses. Using the objective data, the task completion time for each testing block was on average similar as depicted in Fig. 3. An ANOVA analysis of the completion time revealed no significant difference among all testing blocks [$F(4, 49) = 1.65$, $p > 0.05$]. As each block had the same defects, a similar time was thus needed to complete these blocks.

The task accuacy for each testing block gave however a contrast picture, as shown in Fig. 4. An ANOVA analysis of the accuracy revealed a significant difference among all blocks [$F(4, 49) = 24.08$, $p < 0.01$]. Bonferroni post hoc tests inidcated that the difference came from the F_only block, compared to other blocks pairwisely. That is, the F_only block was significantly less accurate than all other testing blocks. Hence, the vibrotactile cue enhanced the accuracy of detecting defects. A comparison between all above results and the corresponding ones in the existing work was to validate our replication of the visual scene, interactive task and cues in the VE.

Table 1. The results of ANOVA analyses among all testing blocks.

Subjective data	Testing Blocks (mean ± standard deviation)					ANOVA	
	V_ co	V_ dis	F_ only	FV_ co	FV_ dis	*F(4, 49)*	*p < 0.05*
Usefulness (%)	67 ± 18	60 ± 22	65 ± 20	65 ± 15	60 ± 24	0.65	—
Effectiveness (%)	63 ± 17	57 ± 19	53 ± 23	61 ± 20	56 ± 23	0.92	—
Pleasure (%)	65 ± 18	61 ± 22	60 ± 22	69 ± 22	64 ± 23	0.83	—
Workload	126±38	138±26	145±28	144±24	139±33	1.79	✓

As summarized in Table 1, ANOVA analyses of the subjective data revealed that no significant difference existed among the testing blocks for perceived usefulness, effectiveness and pleasure. The workload gave however a significant difference. Bonferroni post hoc tests yieded that the difference arose from the V_co vs. F_only blocks [$F(1, 9) = 1.84$, $p < 0.05$] and the V_co vs. FV_co blocks [$F(1, 9) = 2.46$, $p < 0.05$].

Since the participants were instructed to favor the vibrotactile cue over the force cue, their data were biased towards the reliance on the vibrotactile cue. For the reliance-biased data, MLE and mean-shifted MLE were applied to the task accuracy of each testing block. This estimated Gaussian-distributed observations of the inidvisual cues, and yielded Gaussian-distributed observations and predictions of their cue collaboration. The observations and predictions were derived for the co-located and dis-located settings, as presented respectively in Figs. 5(a) and 5(b).

The same MLE and mean-shifted MLE estimations were carried out for the reliance-unbiased data from the existing work [11]. The estimations gave Gaussian-distributed observations and predictions as depicted in Figs. 6(a) and 6(b), correspoding respectively to the co-located and dis-located settings. Comparisons between Figs. 5 and 6 allowed for verifying the applicability of mean-shifted MLE.

V. Discussion

In this study, the outcomes of both task completion time and task accuracy agreed with those in the existing work [11]. This validates that our replication of the visual scene, interactive task and cues was as good as their originals. The reliance biased towards the vibrotactile cue seems to have no effect on both the completion time and task accuracy. The effect of the vibrotactile

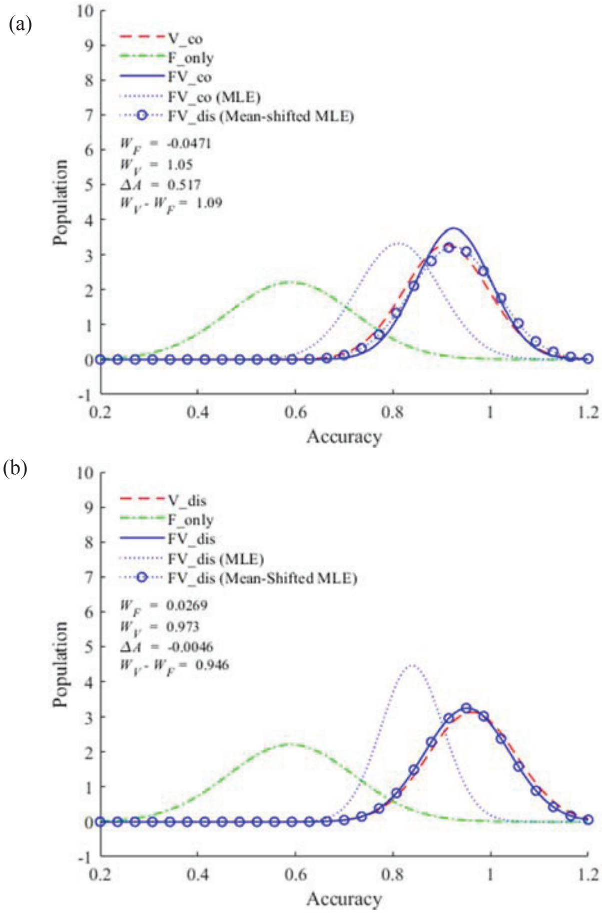

Fig. 5. Estimations of MLE and mean-shifted MLE on the reliance-biased data in the (a) co-located and (b) dis-located settings.

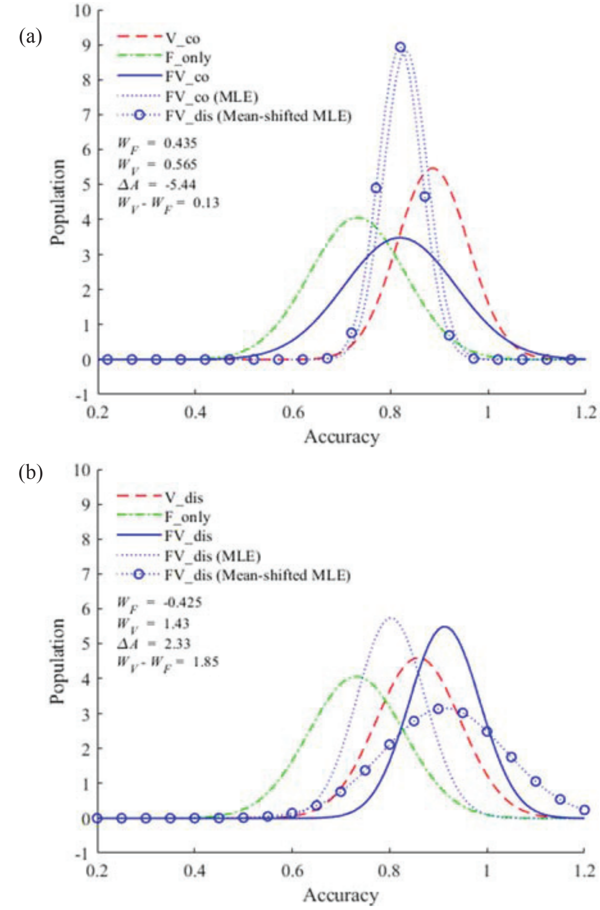

Fig. 6. Estimations of MLE and mean-shifted MLE on the reliance-unbiased data in: (a) the co-located and (b) dis-located settings.

cue on the task accuracy conformed well with that in the existing work and other studies on sensing surfaces with tactile cues [17].

Moreover, our ANOVA analyses of the subjective data revealed similar trends of the F_only block as in the existing work [11]. The F_only block was on average less effective and pleasurable compared to other blocks, even though their means were not statistically differentiable. Although the means of workload was higher in this study than in the existing work, the standard deviations of the workload were at the similar level for all corresponding blocks. Notwithstanding, the standard deviations of usefulness, effectiveness and pleasure were larger in this study than in the existing work. This might result from the reliance biased towards the vibrotactile cue.

When interpreting observations of the cue collaborations, MLE failed for three cases presented in Figs. 5(a), 5(b), and 6(b). One exception was the case of a reasonable mean-match as shown in Fig. 6(a). The MLE predictions of the collaborations based on the reliance-biased data unmatched their corresponding observations, as seen in Fig. 5. The observations were close to those of the V_co and V_dis blocks, as well of the mean-shifted MLE predictions. The closeness was especially pronounced in the dis-located setting, as depicted in Fig. 5(b). The participants might entirely ignore the force cue that was delivered at a dis-location from the vibrotactile cue, making its mean-shifted MLE prediction plausible.

The participants utilized however the force cue to a certain degree, when the cue was delivered at a co-location with the vibrotactile cue. This manifested as an amplitude mismatch between the observation of the cue collaboration and the mean-shifted MLE prediction, as depicted in the case of Fig. 5 (a). The similar amplitude mismatch existed in the dis-located setting, as seen in another case of Fig. 6 (b). While differing from the deliveries of the cues (co-located vs. dis-located), the participants in both cases favored clearly the vibrotactile cue but yielded the amplitude mismatches. Compared to MLE, mean-shifted MLE elucidated well the observations of the cue collaborations in all 4 cases of Figs. 5 and 6. Each case interpretable by MLE and/or mean-shifted MLE, nevertheless, had an amplitude mismatch.

To examine the amplitude mismatch, we regressed the mean difference (ΔA) obtained using Eq. (3) against each mean-shifted weight (W_V or W_F) for all reliance-biased and –unbiased cases. As depicted in Fig. 7, the regression between ΔA and W_V (or W_F) follows a Sigmoidal curve [18]:

$$\Delta A = \frac{\alpha}{1+e^{-\beta(W-W_0)}} + C \ , \tag{5}$$

where W represents a mean-shifted weight; and the parameters of α, β, W_0 and C are respectively the upper limit of ΔA, a positive coefficient, a constant weight at which ΔA equals to $\alpha/2$ and a constant. Using the Gauss-Newton method [18], a non-

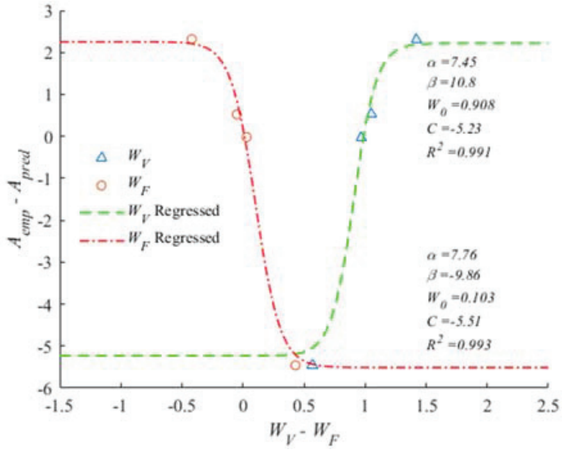

Fig. 7. Sigmoidal fit of the force and vibrotactile weights with different in amplitude of accuracy distributions

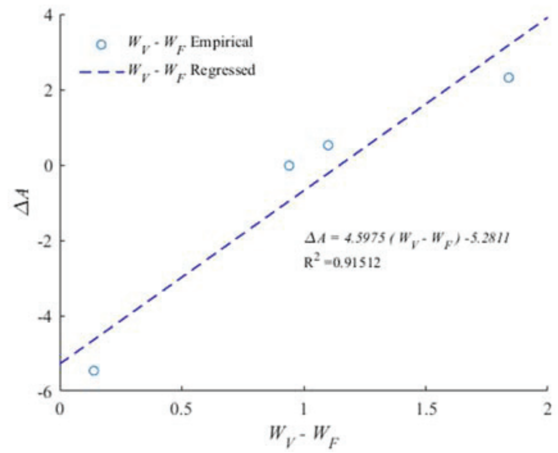

Fig. 8. Linear fit of difference of force and vibrotactile weights with different in amplitude of accuracy distributions

linear least square fitting of the available ΔA against W_V yielded a regression coefficient $R^2 = 0.99$ and the parameters of Eq. (5), as presented in Fig. 7. So did the fitting of all ΔA against W_F with its fitting parameters. The relative symmetry of the two sigmoidal curves implies that there might be a linear relationship between ΔA and the difference of W_V and W_F. This linear relationship is evident by a least square regression, as shown in Fig. 8 with $R^2 = 0.92$. This indicates that the function f in Eq. (4) is a linear relationship between ΔA and W_V - W_F. This relationship suggests that the collaboration between vibrotactile and force cues might not be necessarily additive for humans to undertake 3D interactive tasks. More ΔA values would be imperative for validating the linear relationship in the future.

As given in Eq. (1), MLE assume an entirely additive effect among cues in collaboration. That is, the cues reinforce positively by each other. This might be true in the collaboration between visual and haptic cues [2]. So do other cue collaborations between visual and auditory cues, as well between force and position cues [2], [9], [10]. Although remedying the mean mismatches resulted from MLE, mean-shifted MLE took the same additive assumption as MLE. This explains the amplitude mismatches produced by both MLE and mean-shifted MLE, as depicted in Figs. 5 and 6. Thus, the interpretation of the collaboration between the vibrotactile and force cues might need a model without additive assumptions.

VI. Conclusion

Replicating the existing work [11], we proposed mean-shifted MLE to handle the mean and amplitude mismatches produced by MLE for the collaboration between vibrotactile and force cues. While mean-shifted MLE remedied the mean mismatch, the examination of the amplitude mismatch yielded promisingly a linear relationship between the mismatch and the difference of mean-shifted weights. Future work needs to acquire sufficient cases to gain insights into multi-sensory collaboration in virtual environments.

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