2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

Free manipulation facilitates bimanual integration in a haptic pliers' size discrimination task *

Q. Xu, G. Baud-Bovy, *Member, IEEE*

***Abstract*— Humans can accurately distinguish the shape of objects through haptic interaction. In the present study, we investigated the haptic perception of the size of large pliers held with both hands. An haptic size discrimination task was conducted in three experimental conditions: (1) a free bimanual condition where the pliers were free to move in the fronto-parallel plane; (2) a bimanual constrained condition where the position of the rotation axis was fixed; and (3) a one-hand condition with the position of the rotation axis fixed. The first objective was to find out whether the perception of the pliers' size is affected by the constraint on the pliers' rotation axis. The second objective was to investigate the integration of bimanual information in this task. We found that the discrimination threshold was lower in the free condition than in the bimanual constrained condition. This finding indicates that bimanual physical interaction in the free condition can facilitate bimanual integration during haptic exploration. We propose that bimanual physical interaction could facilitate the construction of a mental representation of the pliers' size from the sensory cues that are collected by the two hands during haptic exploration.**

I. Introduction

While many actions in daily life involve articulated objects, such as opening doors, handling joysticks, or using scissors, our ability to perceive the kinematic properties of this class of objects has been little studied. In this study, we investigate the ability of people to discriminate haptically the size of large pliers. From a kinematic point of view, pliers can be viewed as two shafts connected by a revolute joint. The pliers' size corresponds to the distance between the revolute joint and the hand positions on the shafts. During manipulation, the revolute joint constrains the movement of the hands along a circular path around the instantaneous rotation axis.

The manipulation of pliers present several characteristics that differ from the exploration of the shape of grounded objects, where the hand or fingers move over the surface of the object. First, pliers that are typically held bimanually and are free to move in space. Any force applied by one hand is immediately transmitted to the other hand. In contrast, when the objects are grounded, their position is fixed and the force applied by one hand is transmitted to the ground/structure supporting the rotation axis. Second, the manipulation of pliers is not limited to the open-close movement around the revolute joint but also entails more general translations and/or rotations in space since hand-held pliers are not rigidly fixed to the ground. A consequence is that the absolute position of the hand cannot give direct information about the object shape or degree of curvature in this case. The first objective of this study is therefore to find out whether the perception of the pliers' size changes when the pliers are "free" to move with respect to a "constrained" condition where the pliers' rotation axis is fixed.

A second objective is to investigate the integration of bimanual information in this task. Previous studies have found contrasting results on bimanual integration. Squeri et al. did not find evidence supporting the integration of bimanual in a curvature discrimination task [1]. In this study, the participants grasped one or two vertically oriented handle(s), which were moved along a curved trajectories in the horizontal plane. In contrast, Panday et al. found evidence that information from both hands is integrated when participants must discriminate the size of a cylinder [2]. In their study, participants explored two circular surfaces that were placed at a distance that corresponded to a virtual cylinder. Control experiments indicated that the improvement in the bimanual condition relative to the unimanual one was related to the integration of curvature information provided by the surfaces rather than to position cues such as the distance between the two hands. They also argued that bimanual integration of positional information might not be very advantageous in daily life because the position of the left and right hand are not necessary correlated when touching or lifting objects. To address this issue, we measured the ability of people to perceive the length of a rotating shaft with one hand. This condition was similar to the bimanual constrained condition except that only one hand is used. Note that it is necessary to fix the joint position in the uni-manual condition in order to constrain the hand movement along a circular trajectory. A secondary question is whether bimanual integration changes when the pliers are allowed to move freely in space with respect to when the position of the joint is fixed.

Previous research on the perception of hand-held objects has revealed that a variety of kinetic and kinematic cues can be used to perceived the length of the object without vision. Turvey and collaborators have shown that people can identify the length of a stick from kinetic cues such as the static torque when holding the object at rest [3] or the moment of inertia when wielding the object [4]. To remove these cues, all pliers had the same mass. Moreover, the movements of the pliers were restricted to the vertical (fronto-parallel) plane. Participants were not allowed to move the hands over the pliers to feel directly the distance between the handle and the rotation axis. Under these conditions, the main cues to

* Research is supported by the EU PACE project (Hz 2020, No 642961).

Q. Xu and G. Baud-Bovy are with the Robotics, Brain and Cognitive Sciences Unit, Istituto Italiano di Tecnologia, via Morego 30, Genova (qinqi.xu@iit.it).

G. Baud-Bovy is also with the Faculty of Psychology, Vita-Salute San Raffaele University and the Unit of Experimental Psychology, Division of Neuroscience, IRCCS San Raffaele Scientific Institute, via Olgettina 60, 20132, Milan, Italy (corresponding author: gabriel.baud-bovy@iit.it).

978-1-5090-1425-5/17/$31.00 ©2017 IEEE

judge the pliers' size are related to the radius of curvature of the circular path around the instantaneous axis of rotation, which can be sensed via the hand positions and orientations during the opening and closing movements.

With respect to kinematic cues, previous research has shown that a variety of cues can be used to perceive the radius of curvature of a circular trajectory, such as the change in the position of the hand or finger when moving along the object (0^{th}-order cue), the orientation of the tangential plane (1^{st}-order cue) or the local curvature of the surface (2^{nd}-order cue), which can be felt by deformation of the finger pads and/or the shape of the hand [5]. The importance of each cue depends on the object size and/or the scale of exploratory movements [6]. For small scale movements (< 2 cm), 2^{nd}-order cues such as the curvature are most informative while 0^{th}-order cues are like to be used when exploring large objects (> 0.75 cm). For middle-sized objects like our pliers with a reference length of 50 cm, 1^{st}-order cues are the most important [6, 7]. In our study, the hand position and orientation correspond to 0^{th}- and 1^{st}-order cues respectively. 2^{nd} order cues were missing.

The following sections report the method and results. Then the questions raised in this introduction are addressed again in the discussion.

II. Method

A. Subjects

The study comprised two experiments. The first experiment included 18 participants (10F, 8 M, 28.1 ± 6.7 years). The second experiment included 20 participants (7 F, 13 M, 29.7 ± 9.9 years). Nine participants did both experiments. All participants were right-handed and none of them reported to any known hand deficits. All the subjects were naive to the purpose of the experiment and gave their informed consent.

B. Apparatus and experimental procedure

During the experiments, the participant sat in front of a metallic frame which was used to limit the range of motion of the hand(s) and to fix the pliers' rotation axis when needed (see Fig. 1).

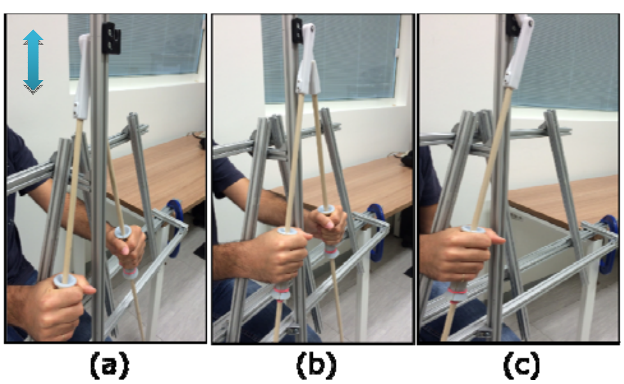

Figure 1. Three experimental conditions are employed: (a) two-hand free motion (b) two-hand constrained (c) one-hand constrained.

The pliers used in this experiment were formed by two wooden sticks (length 80 cm; diameter = 10 mm) connected by a 3D-printed rotary joint. Cylindrical 3D printed ergonomic handles with a groove marking the position of the index finger could be fixed at different positions on the wooden shafts. Five pliers with the handle set at different positions along the shafts were used in this study.

During each trial, subjects manipulated two pliers held with a power grasp in succession. Starting with the hands near the central position, they opened and closed the pliers until touching the limit of the workspace three times. At the end of each trial, they had to report verbally which one of the two pliers was longer than the other (two-alternative-forced-choice task).

The method of constant stimuli was used to obtain the psychometric function. For the standard pliers, the distance between the rotation axis and the handle was fixed at 50 cm. For the comparison pliers, this distance varied from 36 to 64 cm in 7 cm steps for the first experiment, and from 34 to 66 cm in 8 cm steps for the second experiment. Each one of the 5 comparison stimuli was presented 10 times in each condition. The order of presentation of the comparison stimuli was randomized within blocks of five trials that included the five possible comparison stimuli. The presentation order of the comparison and standard stimuli within each trial was also randomized.

C. Experiments and experimental conditions

In the first experiment, the participants were given instructions including a drawing of a pair of pliers of different sizes. The instructions indicated that the participant would manipulate each pliers successively and that the task was to identify whether the first or second pliers was bigger. Then, the participants were blindfolded and wore sound isolating headphones during the whole duration of the experiment. No feedback about their responses was given during the experiment.

In the second experiment, a training section was introduced to familiarize the participants with the task and stimuli. First, the participants were shown the pliers and could manipulate them before being blindfolded. Then, the participants were given 16 practices with a feedback on their responses at the beginning of each condition. These practice trials included the standard pliers (50 cm), which was compared to the other pliers four times in a random order. When the participants responded erroneously during the practice trials, they were given back the two pliers in order able to manipulate them for a second time with the knowledge of which one was longer. No feedback was given during the rest of the experiment.

The experiments included three conditions:

- In the "free" condition, the pliers were held with both hands. Movements outside the fronto-parallel plane were prevented by inserting the revolute joint in the slot of structural beam which allowed it to slide along the vertical direction.
- In the "constrained" condition, the rotation axis of the pliers was fixed. The height of the rotation axis was adjusted as a function of the size of the pliers so as to keep the same hand initial position (see Fig. 2, left panel). The pliers were held with both hands like in the free condition.

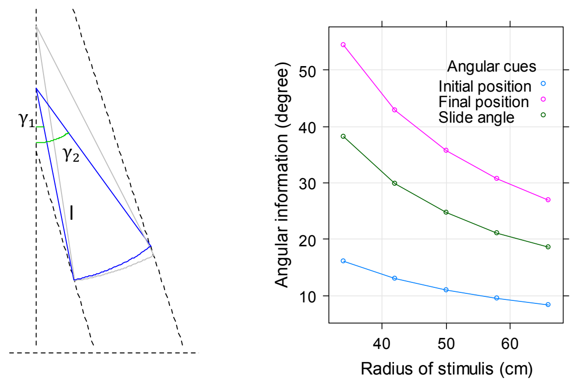

Figure 2. *Left:* Schematic representation of the frame. The range of motion of two different pliers is represented in the constrained conditions. *Right:* Relationshipw between the radius of curvature and other angular cues for plier discrimination.

- In the "one-hand" condition, the pliers' rotation axis was fixed to the frame as in the constrained condition but only one hand was used.

Each participant performed the three conditions. The order of presentation of the conditions was counterbalanced across participants.

D. Kinematic cues and discrimination thresholds

When manipulating the pliers, the hands describe a circular trajectory with a constant curvature around the instantaneous axis of rotation. The curvature is the reciprocal of the radius (l) of curvature, which is defined by the distance between the handle and the rotation axis, i.e., by the pliers' size. At each point along the trajectory, the angle with respect to the vertical defines the local attitude. The limited range of motion defines a circular sector, whose arc correspond to the slide angle ($\gamma_s = \gamma_2 - \gamma_1$), i.e. to the difference between the local attitude at the final (γ_2) and initial (γ_1) positions (see Fig. 2).

For pliers with radius of curvature ranging from 36 to 64 cm, the slide angle limited by the metallic frame varies from 18.550° to 38.221° (one-side), whereas the local attitude changes from 8.399° to 16.150° at initial position and from 26.950° to 54.371° at final position depending on the pliers' size. Fig. 2 shows the relationship between radius of curvature and the angular cues.

For each participant and condition, we fitted a logistic function to the participants' responses to model the probability of judging the comparison stimulus bigger than the standard. The logistic function was fitted to the plier radius of curvature, slide angle, initial and final local attitude. By definition, the Point of Subjective Equality (PSE) corresponds to the pliers' size that is judged to have the same size as the reference pliers. The Discrimination Limen (DL) corresponds to the size difference between the PSE and the pliers' size that is judged larger than the reference pliers in 75% of the trials. The PSE and DL were computed for the radius of curvature, slide angle, initial and final local attitude.

E. Statistical analysis

To compare the threshold across conditions, we used the following linear mixed effects model:

$$DL_{ij} = \mu + t_j + \alpha_i + (\beta + \alpha\beta_i + b_j)x + \varepsilon_{ij} \tag{1}$$

where the fixed effects include the global intercept μ, the condition effect α_i (i = 1, 2, or 3), the slope β for the condition position x (x = 1, 2 or 3) in the presentation order and the interaction $\alpha\beta_i$ between the condition and slope. The random effects include an intercept t_j and slope b_j terms for each subject (j = 1, .., N) in addition of the residuals ε_{ij}. The correlation between the intercept and slope terms was not constrained. Because the dataset does not include replications, it is not possible to include a random effect for the condition or for the interaction. All analyses were conducted with R [8]. The mixed-effect model was fitted using *lmer* function [9], Kenward-Roger approximation for the degrees-of-freedom was used to compute the p values of the fixed effects [10]. Tukey's pairwise comparison tests were computed with *lsmeans* function from the results of the linear mixed-effect model [11]. All tests are two-tailed.

F. Optimal integration

To test whether the cues from the right and left hands are optimally integrated in the bimanual manipulation, we used an optimal cue combination or Maximum Likelihood Estimation (MLE) model [12]. In this model, the threshold variance in the bimanual estimation is determined from the threshold variance in the individual hands:

$$\sigma_B = \frac{\sigma_L^2 \sigma_R^2}{\sigma_L^2 + \sigma_R^2} \tag{2}$$

where the relationship between thresholds and variance is:

$$\frac{T_L^2}{T_R^2} = \frac{\sigma_L^2}{\sigma_R^2} = \frac{w_L}{w_R} = 1 \tag{3}$$

If we assume that the two hands contribute equally (see Discussion), the prediction of bimanual discrimination threshold T_B is:

$$T_B^2 = \frac{T_L^2 T_R^2}{T_L^2 + T_R^2} = \frac{T_R^2}{2} \tag{4}$$

According to the model, the discrimination threshold of bimanual manipulation should be $1/\sqrt{2}$ of that of one hand. By comparing the measurement to the proposed optimal value, we can see whether the perception information from two hands are integrated in an optimal way.

III. Results

The individual thresholds measured in the first experiment were extremely variable. In particular, half (50%) of the participants had a large (DL > 25) or negative threshold in one of the conditions of this experiment. The performance in the second experiment which involved a preliminary training was markedly better: only three participants (15%) had a flat or negative slope in one of the three conditions (two-sided χ^2-test for equality of proportion with continuity correction, $\chi^2(1)$ = 3,873, p = 0.049). Individuals who participated to both experiments improved their performance. In particular, the four participants in this group who had a very large or negative threshold in the first experiment were able to perform well the task in all conditions the second time.

TABLE I. CORRELATION BETWEEN THRESHOLD RANK AND CONDITION ORDER

Cond. order	Threshold rank: Excluded group (N=12)			Threshold rank: Included group (N=21)		
	1	2	3	1	2	3
1	2	4	6	5	8	8
2	3	5	4	7	8	6
3	7	3	2	9	5	7

A close look at the data showed that the worse performance typically happened at beginning of the experiment. To confirm this observation, we ranked the performance of each subject in each condition from 1 to 3 and compared it to the condition order. Conditions with a negative slope were ranked last. Then we divided participants into two groups according to their worst performance. The first group included participants with a negative threshold or a threshold larger than 25 cm in one condition. Table I (left panel) shows that the performance and condition order are negatively correlated. This order effect is confirmed by Spearman's rank correlation test (r = -0.375, p = 0.024). The second group of participants is formed by the participants who had a threshold below 25 cm in all three conditions (N = 21).For the five participants who satisfied this inclusion criterion in both experiments, only the performance in the second experiment was retained to avoid repeated measures in this group (which explains why the total number is 33 and not 38 in Table I). For this group, Spearman's rank correlation test was not statistically significant (r = -0.119, p = 0.353).

A. *Effect of exploration condition*

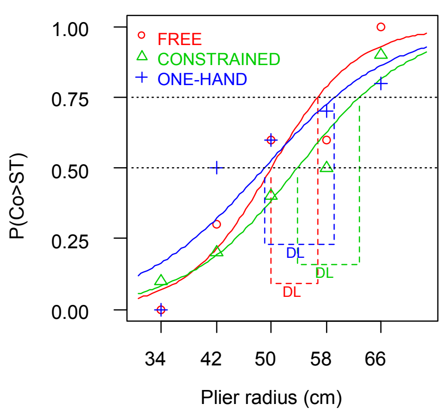

Figure 3. Illustration of psychometric curves for one subject. The DL is largest in the ONE-HAND and CONSTRAINED condition.

Fig. 3. illustrates an example of how the threshold values were obtained from the fitted psychometric functions for one subject. The thresholds at which subjects were able to identify 75% of the stimuli are found to be 6.73, 9.01, 10.18 cm respectively for bimanual manipulation with a free moving plier, bimanual manipulation with a fixed rotation axis, and one hand manipulation with a fixed rotation axis.

To compare the three conditions, we excluded all participants with a very large (DL > 25 cm) or negative thresholds in one or more of the conditions because they did not (yet) perform the task as asked (see Discussion).

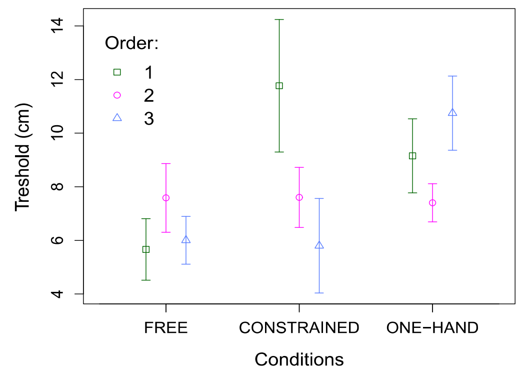

Figure 4. Interaction effect of conditionand order in discrimination threshold. The vertical bars corresponds to the standard error (SE).

Moreover, from an estimation point of view, threshold values above 25 cm are not reliable given the range of stimuli used in this study. All following analyses are conducted on a group of participants who performed reasonably well in all three conditions ("included group" in Table I, N= 21). The results are similar if conducted only with the well-performing participants of the second experiment (N = 17).

Fig. 4 shows the average values of the radius of curvature thresholds in each condition. The results are furthermore split according to the condition order. A linear mixed-effect model introduced in the previous section is used to assess the condition and the order effects on the discrimination thresholds. The results for the radius of curvature and sliding angle thresholds show a significant effect of the condition (F(2, 52.19) = 3.91, p = 0.026) and interaction between condition and order (F(2,53.87) = 3.75, p = 0.030). The main order effect was not statistically significant (F(1,22.78) = 0.91, p = 0.351).

This analysis was followed by Tukey multiple comparison tests that contrasted the three exploration conditions pairwise. Significant differences were found only between the free movement condition and uni-manual manipulation with fixed axis (t(36) = 2.47, p =0.047), and between the free movement condition and bimanual manipulation with fixed axis (t(39)=2.28, p = 0.071). The difference between the uni-manual and bimanual conditions with fixed axis was not statistically significant (t(37) = -0.18, p = 0.982).

TABLE II. THRESHOLDS EXPRESSED IN FIVE CUES

Cues	FREE	CONSTR.	ONE-HAND
Radius of curvature (cm)	6.33±2.92	8.59±5.71	8.93±3.16
Slide angle (γ_2 - γ_1, deg)	3.42±1.81	4.65±2.87	5.26±2.38
Angular attitude (γ_2, deg)	4.85±2.58	6.57±4.04	7.39±3.33

Similar analyses were conducted with the other available cues with similar results. Table II reports the mean discrimination thresholds in terms of the radius of curvature, final angular attitude, and slide angle.

We also compared the discrimination thresholds of each subject with the information gathered from self-report rating the difficulty of each condition. A rank correlation between the threshold and confidence rating didn't reveal any correlation between the subjective estimate of the condition difficulty and the actual performance ($p = 0.7$).

B. Bimanual integration

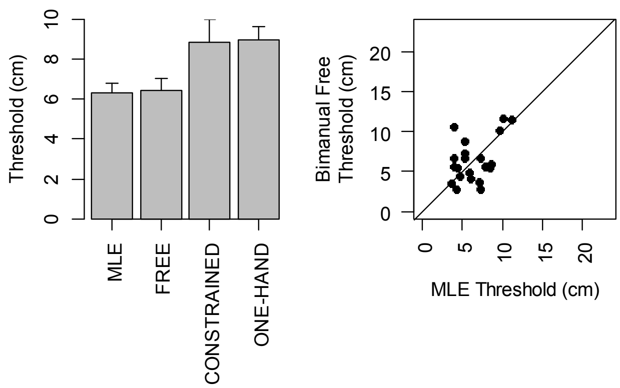

Figure 5. *Left:* Average threshold values in bimanual (CONSTRAINED and FREE), unimanual (ONE-HAND) conditions and average predicted threshold (MLE). The vertical bars corresponds to the SE. *Right*: Comparison between measured and predicted individual thesholds.

The threshold predicted by Maximum Likelihood Estimation (MLE) corresponds to the ONE-HAND threshold $/\sqrt{2}$. Fig. 5 shows that the MLE threshold and FREE threshold (paired t test: $t(20) = 0.2122$, $p = 0.824$). In contrast, the constrained threshold was markedly larger (paired t test: $t(20) = 2.125$, $p = 0.046$). At the individual level, the MLE thresholds were correlated with the thresholds in the FREE condition (Pearson coefficient of correlation: $r = 0.459$, $p = 0.036$) but not with the threshold in the CONSTRAINED conditions ($r = 0.208$, $p = 0.365$).

IV. Discussion

The first objective of this study was to find out whether holding the pliers “naturally” with two hands made a difference with respect to a “constrained” condition where the pliers’ rotation axis is fixed. Our results show that people can discriminate the length of hand-held pliers by simply opening and closing them. Moreover, we found that the best performance is obtained in the free condition, where the position of the rotation axis is not fixed. The value of the pliers’ size discrimination thresholds in this condition (~6 cm) is in the same range as the discrimination thresholds (~5 cm) found, for example, by Sanders and Kappers [13] for a cylindrical stimulus with a radius of curvature of 40 cm [2].

Half of the participants in the first experiment performed poorly but their performance tended to improve across conditions. Almost all participants performed reasonably well in the second experiment which included a brief training with feedback. These observations suggest that the participants who performed poorly had probably some difficulty to attend the proper cue(s) and/or process them correctly at the beginning of the experiment.

It might also be noted that discrimination thresholds for the wrist flexion/extension and abduction/adduction are about 2.15° and 1.52° respectively [14], which is markedly lower than the angular thresholds measured in this study (slide angle or local attitude, see Table II). In other words, the level of performance observed in this study is well within the discrimination ability of the haptic system.

A. Sensory cues in the free and constrained conditions

It is important to analyze carefully the differences between the free and constrained conditions. In the free condition, the pliers’ position is not constrained and the two hands can move freely in the frontal plane. Moreover, the vertical force produced by one hand can be felt by the other hand. In contrast, these characteristics are completely absent in the constrained condition where the position of the pliers’ rotation axis is fixed, where the hand trajectory limited to a circular path and where the force is not transmitted between the two hands but transmitted to the structure holding the pliers.

It should be noted that the motion of the pliers and/or the force transmitted between the two hands did not provide additional cues about the pliers’ size in the free condition. In fact, arguably, the constrained condition might have provided more information about the pliers’ size. In the free condition, the absolute position of the hands cannot be a cue since they are free to move in the frontal plane; the radius of curvature must be inferred from the relative position and orientation of the two hands. In contrast, when the rotation axis is fixed, the position of the hand could give information about the pliers’ size. Although we adjusted the position of the rotation axis as a function of the pliers’ size to remove this cue (see Methods), the adjustment was not perfect because only the initial hand positions coincided for pliers of different sizes (see Fig. 2, left panel). Thus, the hand trajectories in the constrained condition could provide positional cues that were absent in the free condition.

B. Bimanual Integration

The second objective was to investigate the integration of bimanual information in this task. To compute the discrimination thresholds predicted by the optimal integration hypothesis [12], we measured the thresholds for the right hand and assumed that it was the same for the left hand. This assumption is supported by results of a previous study on the curvature and object size perception which revealed no significant difference between the two hands in the unimanual conditions [2]. It might also be noted that we used the same unimanual constrained condition to predict the optimal performance in the free and bimanual constrained conditions. The reason is that it is necessary to fix the rotation axis in the unimanual condition to provide kinematic cues about the pliers’ size. Without fixing the rotation axis, the hand is free to move and the task cannot be done unless the participant uses kinetic cues [3, 4] which were lacking by design in our study.

As noted previously, participants performed better in the free condition than in the constrained condition. In fact, the results in the free condition were very similar to those predicted by the optimal integration hypothesis while the results in the constrained condition were similar to those obtained in the unimanual condition.

Our results apparently contradict the results of Squeri et al. who did not find bimanual integration in a curvature perception task [1]. One difference between the two studies is that our stimuli provided not only positional (0^{th}-order) information but also angular (1^{st}-order) information. It could be tempting to conclude that angular information (1^{st}-order) cue like curvature (2nd-order cue) are integrated [2]. However, bimanual integration was absent or much weaker in the constrained condition, which also included 0th-order and 1st – order cues. Therefore, the mere presence of angular information (slide angle or local attitude) is not a sufficient cause for integration to happen. Our results also indicate that curvature information (2nd-order cue) is not necessary for integration to happen [2].

To understand our results and those of Squeri et al. [1], it is important to emphasize the main difference between the free and constrained conditions, which consisted in the fact that the two hands were free to move and interacted physically only in the free condition. In this respect, it is noteworthy that the two hands did not interact physically in [1] because the trajectories were constrained by the robot which moved the two hands passively.

To achieve bimanual integration, Panday et al. [2] emphasized the importance that the response be based on the perceived shape of the object, which presumably involve processes that integrate information from both hands to build a higher level representation of the object's shape. A possibility is that such a process is facilitated in the free condition where the two hands interact physically in a more natural manner. In other words, bimanual physical interaction might contribute to the construction of a unitary and more accurate high-level representation of the pliers from the sensory cues that collected from the two hands during the exploration.

C. *Discrimination versus perception of the pliers' size*

In theory, simply discriminating between the size of two pliers requires less cognitive processing than actually estimating their size. As a matter of facts, perceiving the pliers' size requires a mental representation of the position of the rotation axis relative to the hand position that is not immediately available in the haptic modality; the rotation axis position must be somehow extrapolated from the positions and orientations of the two hands, or from the successive position and orientation of a single hand. Such a mental representation is not necessary to discriminate between two pliers where it might be enough to compare directly the local attitudes or slide angles achieved with the two pliers. That said, our task required the participants to indicate which one of the two pliers was bigger, not only whether they were the same or different. Responding to this question requires one to correctly associate the sensory cues with the pliers' size.

This observation might also explain why the free condition, where the creation of a mental model of the object might be facilitated, would lead to a better performance. Clearly additional evidence is needed to support this hypothesis. For example, it might be interesting to find out whether this difference between the free and constrained conditions applies not only to articulated objects, like pliers, but also to simpler object like cubes.

V. CONCLUSION

Our findings add to the debate on the nature of multi-sensory integration. Recent work suggests that multi-sensory integration can be affected by high-level processes such attention and/ consciousness [15-17]. While this debate is focused on the integration of information from different sensory modalities, we believe that it is also relevant with respect to the integration of different sensory cues within the same sensory modality, such as proprioceptive information coming from the left and right hands. In this respect, our study show that physical interaction might be a factor that facilitates integration of information from both hands during bimanual object manipulation.

REFERENCES

[1] V. Squeri, A. Sciutti, M. Gori, L. Masia, G. Sandini, J. Konczak. "Two Hands, One Perception: How Bimanual Haptic Information Is Combined by the Brain," *J. Neurophysiology*, vol. 107, no. 2, pp. 544-550, 2012.

[2] V. Panday, W. M. Bergmann Tiest, W. M., A. M. L. Kappers "Bimanual Integration of Position and Curvature in Haptic Perception," *IEEE Trans. on Haptics*, vol. 6, July-Sept. 2013.

[3] M. T. Turvey, G. Burton, E. L. Amazeen, M. Butwill, C, Carello, "Perceiving the width and height of a hand-held object by dynamic touch," *J. Exp. Psychology: Human Perception and Performance*, vol. 24, no. 1, pp. 35–48, Feb. 1998.

[4] M. T. Turvey and C. Carello, " Obtaining information by dynamic (effortful) touching". *Philosophical Transactions of The Royal Society B Biological Sciences*, 366(1581), pp. 3123-32, Nov. 2011.

[5] S.C. Pont, A.M.L. Kappers, J.J. Koenderink, "Haptic curvature discrimination at several regions of the hand." *Perception & Psychophysics*, vol. 59, no. 8, pp. 1225–1240, Dec. 1997.

[6] M.W.A. Wijntjes, A. Sato, V. Hayward, A.M.L. Kappers, "Local Surface Orientation Dominates Haptic Curvature Discrimination," *IEEE Trans. Haptics*, vol. 2, no. 2, pp. 94-102, Apr.-June 2009.

[7] S. C. Pont, Astrid M. L. Kappers, and Jan J. Koenderink, "Similar mechanisms underlie curvature comparison by static and dynamic touch". *Perception & Psychophysics*, vol. 61, no. 5, pp. 874-894, 1999.

[8] R Core Team, "R: A language and environment for statistical computing," *R Foundation for Statistical Computing*, Vienna, Austria. URL, https://www.R-project.org/, 2015).

[9] D. Bates, M. Maechler, B. Bolker, S. Walker, "Fitting Linear Mixed-Effects Models: Using lme4," *Journal of Statistical Software*, vol. 67, no. 1, pp. 1-48, 2015.

[10] M. G. Kenward and J. H. Roger, "Small Sample Inference for Fixed Effects from Restricted Maximum Likelihood," *Biometrics*, vol. 53, pp. 983-997, (1997).

[11] R.V. Lenth. "Least-Squares Means: The R Package lsmeans," *Journal of Statistical Software*, vol. 69, no. 1, pp. 1-33, 2016.

[12] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415 (6870), pp. 429-433, 2002.

[13] A. F. J. Sanders and A. M. L. Kappers, "Bimanual Curvature Discrimination of Hand-Sized Surfaces Placed at Different Positions," *Perception and Psychophysics*, vol. 68, no. 7, pp. 1094-1106, 2006.

[14] L. Cappello, N. Elangovan, S. Contu, S. Khosravani, J. Konczak, and L. Masia, "Robot-aided assessment of wrist proprioception," *Frontiers in human neuroscience*, vol. 9, no. 198, April, 2015.

[15] T. D. Palmer, A. K. Ramsey, "The function of consciousness in multisensory integration," *Cognition*, vol. 125, no. 3, pp. 353-64, Dec. 2012.

[16] L. Mudrik, N. Faivre, C. Koch, « Information integration without awareness," *Trends in Cognitive Sciences*, vol. 18, no. 9, pp. 488–496, Sep. 2014.

[17] N. van Atteveldt, M. M. Murray, G. Thut,, C. E. Schroeder "Multisensory integration: flexible use of general operations," *Neuron*, vol. 81,no. 6, pp. 1240-53, Mar. 2014.