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Design and Evaluation of a Prototype Tactile Scanner for Active Sensing of Proximal Objects

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Abstract—**Tactile interfaces, that can convey information to humans via tactile feedback, are still relatively rare. In this study we present a prototype 'tactile scanner', that fixes onto a user's arm, and using arrays of capacitive sensors and vibratory motors, provides users with a sense of the proximity of objects near their arm. Through two experiments, we show that the device enables users to detect not just the position of objects, but also estimate their shapes and orientations. Finally, in a third experiment, we compare the user accuracy with the tactile scanner and their accuracy with real touch.**

Index Terms—**Human performance, Tactile devices and display, Human-computer interaction**

I. Introduction

THE spatially extended skin (SES; [1]) paradigm refers to a broad class of interactive systems aiming to enhance their users' spatial awareness by providing them with spatial information through a tactile display. In general, these wearable devices combine array of distance sensors with arrays of tactile transducers distributed across their users' body to feed them back with information about their surrounding environment. In the literature, most of the proposed prototypes correspond to electronic travel aids (ETAs; [2]) which function as "wearable obstacle avoidance systems" designed to guide the user through a safe walking path in a cluttered environment. While ETAs were originally targeted at users presenting visual deficits, a number of author [3]–[5] have interested themselves in the design of ETAs for users without such deficiencies. For example, the ProximityHat [6], the Tactile Helmet [7], [8] and the TactiHelm [9] are head worn ETAs designed to provide their users with proximity warnings when the distance from the user's body to some environmental feature goes below a given threshold. For all three devices, the distance information between the user's body and an obstacle are collected via (ultrasonic) distance sensors distributed at 360° around the user's head and presented using tactile cues (pressure or vibration) on the skin directly below the sensors. In addition to hats, vibrotactile belts [4], [5] and suits [10], have also been proposed as a mean to offer their users' with 360° awareness about their proximity to various environmental features. In term of applications, these devices can help their users to navigate environments in poor visibility conditions, to increase their safety when working in cluttered environments or to monitor their surroundings without relying on sight or audition.

In this study, we propose a new type of device falling under the SES paradigm aiming to enhance a user's spatial awareness. However, in contrast with the aforementioned studies, our prototype is specifically designed to work in the user's reaching space. In particular, to augment a worker's spatial awareness when operating in cramped or cluttered spaces, for example in the undercarriage of an aircraft or an oil rig. In such scenarios, our device aims to enable its user to locate environmental features (a tool for example) with his arms and hands and avoid collisions without diverting his visual attention from the apparatus he is currently working on. In this regard, our prototype is thus more closely related to tactile-visual sensory substitution devices (TVSS; [11]–[13]) which aim to provide blind users with a finer grained picture of their surroundings than ETAs. In contrast with TVSS device however, our prototype is aimed at sighted users, such that our goal is not to substitute to vision but rather to complement to the information it provides and offer the user with an alternate mean to monitor and/or explore their reaching space.

This article is structured as follows. We first present the design and rational for the proposed prototype before presenting the results gathered in three user studies. The first examined the precision with which our prototype enables its users to localize small objects (2cm) in their reaching space. The second quantified both the ability of users to localize as well as identify larger shapes (10cm) using the device. Finally the third study compared the accuracy with which the users performed the first two tasks with the accuracy with which the user might relate the tactile cues provided by the device with a position in external space. We close this article with a discussion on the results and strategies employed by the participants in our study.

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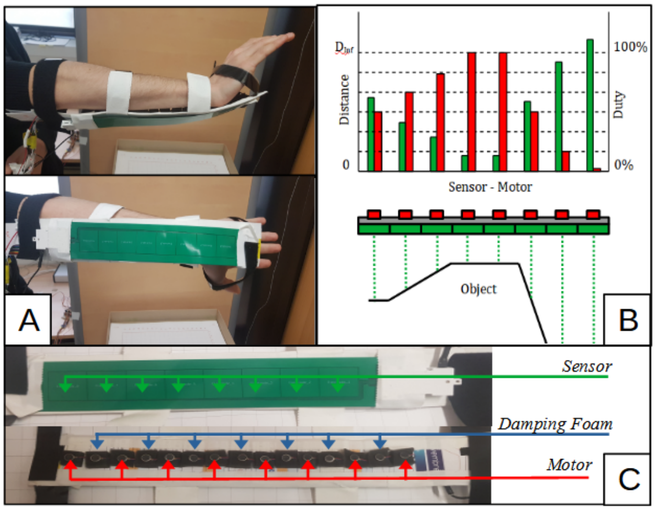

Fig. 1. The Tactile Scanner. A. The device is strapped on the user dominant arm, with the motor array in contact with the skin and the sensors facing away from the limb. B. The distance measured by each sensor (in green) is used to modulate the duty cycle of the motor (in red) located directly beneath it. C. Front (top panel) and back (bottom panel) view of the device.

II. Methods

A. Device

Our *Tactile Scanner* consists in an array of 8 capacitive cells (3x3cm designed by Fogale Sensors) layered with an array of 16 vibratory motors (VC0825B002F from Vybronics - 225Hz) (see Fig. 1). Pieces of cubic sponge are sandwiched between each vibrator and the capacitive array to isolate the motor and prevent the vibration to be transferred to the sensors array as well as nearby vibrators. Overall, this give the scanner dimensions of 30 by 5 cm and 150 grams of weight. This includes velcro straps that enable a user to fix the scanner to his/her forearm. As mentioned above, our prototype is designed for objects detection and avoidance with respect to the arm but a similar paradigm can be employed for other parts of the body.

The distance measurements provided by each capacitive cell is then transmitted to a micro-controller which modulates the amplitude of the motor directly below the cell (or an average between cells for motors located between two cells). In effect, the user is provided with a vibration amplitude which is inversely proportional to the distance of the specific part of the forearm from the object. We chose to modulate the duty cycle of a vibrating motor between 6 different intensities (Fig. 1B), with a stronger vibration indicating smaller distance and vice-versa. Each of these steps representing roughly 5cm in distance between the sensor and the detected object.

While they cannot be used for long range measurements (beyond 1 to 2 meters) our aim to work in the user's reaching space motivates the use of capacitive sensors for a number of reasons. First, capacitive sensors have been previously used with great success in robots for applications similar to ours [14], [15]. In [16] for example, a collision avoidance system for a robotic arm is implemented by wrapping the robot in capacitive cells, allowing it to monitor its proximity to a worker with whom it shares its workspace and thus avoid accidental collisions. Second, in comparison to other sensor technologies such as ultrasonic or laser based, capacitive cells are purely passive sensors consisting in thin metallic sheets. As such, they can easily be shaped in any form and are flexible such as to tightly fit to a user's limbs. Moreover, the fact that these sensors are passive means that they do not require to equip the user with the usual couple of emitter/receiver involved in other technologies, thus allowing to largely reduce the footprint of the device. Third, given that the device is used to monitor the user's reaching space, it is to be expected that the distance of the sensors to other environmental features will generally be small. Among these features, some of them are relevant to the user, for example a toolbox or a door handle, while some other are not and should be ignored by the system, for example the floor, walls or even the user's body itself. In this regard, capacitive sensors easily enable to prune out irrelevant features by ”guarding them”, that is, render them invisible to the sensors by connecting them to an appropriate electric potential. In our experiment, this property is used to ensure that only ”relevant objects” can be detected. In figure 2.A for example, every object in the experimental setup, from the table, surrounding walls and even the participant are guarded and therefore completely invisible to the sensor. Finally, capacitive sensors are non-directional, meaning they do not require to be oriented towards an object to detect it. Given our application, this property is very useful since it allows the user to reach an object of interest by following amplitude gradients across the entire search space and not only when the device is directly facing the object. Furthermore, this property also means that the device cannot suffer from intermittent detection when employed to localize small objects.

B. Participants

22 participants (12 in the first 2 experiments, and 10 in the third experiment) in total participated in the evaluation study for the tactile scanner which included three experiments. All experiments were conducted according to the principles in the Declaration of Helsinki. The subjects gave informed consent prior to the experiment and the experiments were approved by the local ethics committee reviewing studies in Laboratoire d'Informatique, Robotique et Microélectronique de Montpellier (LIRMM, Approval ID: 2201F). The volunteers were orally introduced to the working of the device before it was strapped to their right arm. The oral description was the only information the participant was given about the device and no participant had previous experience with a similar setup before the evaluation.

C. Experiment 1 – Localizing small objects

For experiment 1, the participants stood in front of an elevated table (see Fig. 2A). A checkered sheet of paper (of 2x2 cm cells) served as the search area on the table. The search area rows (Y axis) were indexed from A to R (top to bottom), while the columns (X axis) were indexed from 1 to

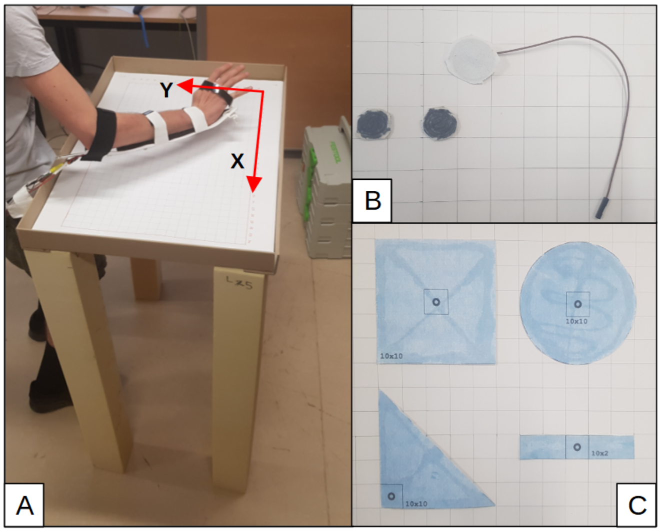

Fig. 2. The experimental setup. A. The participant scan the search area with the haptic scanner in order to find the marker/shapes hidden beneath the checkered sheet. B. The marker used in Experiment 1. C. The 4 shapes used in Experiment 2.

30 (left to right). We ensured both via a selection of material and via guarding that the sheet of paper and the table were invisible to the capacitive sensor.

In each trial of Experiment 1, the participant was asked to locate 3 metallic objects (Fig. 2B) distributed across the search area and under the sheet such that they were not visible to the participant. The participants were required to move their arm over the search area and localize the targets by the vibrations (proximity) they felt. Each participant was presented with eight trials with the 3 target positions drawn from a set of 12 possible configurations. The participants were asked to place paper discs on the search area to indicate their answers in each trial. There was no time limit in the task and they were allowed to relocate (the paper discs) and adjust their answers as many times as they wanted. Once they felt confident in their answer, we recorded the indexes of the cells the participant had marked during his search.

D. *Experiment 2 – Identifying simple shapes*

The second experiment was performed with the same setup as Experiment 1. The experiment procedure was similar to the first with the exception that the participant was tasked with locating flat shapes hidden in the search area. This shape, made of aluminum foil, was semi-randomly selected from 4 possible shapes (a 10x10cm square, a circle with 10cm diameter, a 10x10cm square-triangle and a 2x10cm bar, Fig. 2C). All participants again performed eight trials, with one shape presented in each trial. Each participant experienced each shape at least once. The participants were again given paper versions of the 4 different shapes and were required to place the right shape in the location where they perceived a shape. Similar to Experiment I, the participant had unlimited time to explore the search area and we recorded their response (i.e. the shape they selected and its position and orientation) after they were confident of their answer.

E. *Experiment 3 – Estimating a position from touch*

Experiment 3 measured the accuracy with which humans are able to locate a tactile stimulation on their forearm, and consequently to relate that position on the forearm to a position in external space space. While previous studies have examined the resolution of tactile perception by humans [17], [18], such estimates have been known to be heavily dependent on a wide range of factors (among them the part of the body being stimulated [19] or the properties of the stimulus [20] for example). We therefore decided to include this last experiment to form a baseline that is specific to our experimental settings (location and stimulators). This helped us to estimate the proportion of the errors in Experiment 1 that were a result of "natural" inaccuracy in tactile localization and the proportion that was to be attributed to our device.

This last experiment required participants to put their right arm into an opaque cardboard box (see Fig.5A). Atop the box and in view of the participant, were marked 9 positions spaced by 2cm and numbered from 1 to 9 (starting at the wrist and ending a bit before the elbow). Each participant participated in 15 localization trials. In each trial, the experimenter randomly selected one of the nine position and applied a tactile stimulus at that position onto the participant arm with the same vibratory motor as on the device. The stimulation was presented inside the box and hence the participant could not see where the tactile stimulus was applied. The participants were allowed to move their arm (if they wanted) similar to Experiment 1, and were asked to call out the marking on the box (from 1 to 9) which he/she thinks represents the location of the stimulus in the external space. There was no time limit and the stimulus location remained fixed to the external space during their hand movements. The experiment thus required the participants to localize a tactile stimulus in external space, similar to what they did in Experiment 1. Following the 15 trials, the error between the actual stimulus location and the localization identified by the participant were analyzed to estimate the localization errors exhibited by humans of tactile stimuli (in external space) when the exact point of stimulation is not visible (as it was the case in Experiment 1).

III. RESULTS

A. *Experiment 1 - Localizing Small Objects*

To measure the performance of the participant during Experiment 1, each cell containing the marker (designated hereafter as ground truth) was paired with the closest cell marked by the participants (designated hereafter as response) without repetition (that is every response was paired with a unique ground truth). This procedure was performed for every trial and participant. Finally in the overall data, points further than 3 times the standard deviation across all the couples, were considered as outliers and removed from the analysis. The outliers accounted for less than 2% of the data.

We analyzed both the total detection error in cm, and the contribution of bias as well as the precision (standard deviation) of the detection. We observed that, as hypothesized,

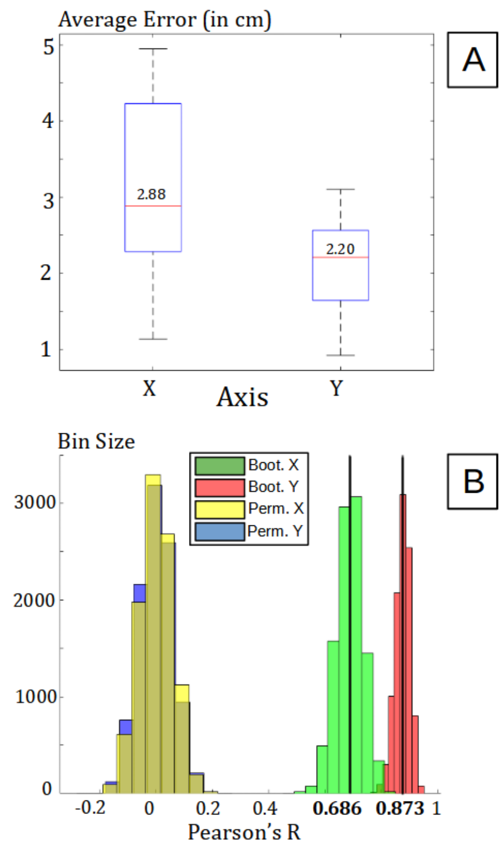

Fig. 3. Performance in Experiment 1. A. The average distance between the ground truth and response couples over the along the X and Y directions averaged across the participants. The red lines indicate the median across participants while the box edges show the 25th and 75th percentile respectively. The error bars indicate the 5th and 95th percentile of the data. B. The distribution of correlation coefficient (Pearson's R) between ground truth and answers (X along the columns, Y along the lines) for couples obtained by bootstrapping (Boot. in red and green) and by permutations (Perm. in blue and yellow). The black line marks the correlation coefficient computed from the experiment data. Total bin size is 10000.

participants intuitively utilized arm movements to localize the marker, making progressively smaller and localized movements before making a final judgment on the object position. Fig. 3A shows the mean distance between ground truth and its paired response along the X (columns) and Y (rows) axes obtained during the experiment for each of the 12 possible configurations, across the participants. We observed a median absolute error of 2.88 cm across participants along the X axis and 2.13 cm along the Y axis. The error along Y was significantly less than along X [t(244) = -4.14, p = 5e-5, d = 0.367]. We observed a slight positive bias along the Y axis (0.36 cm) indicating that participant tend to answer closer to their body. This was however missing significance [t(244) = 1.84; p = 0.06; d = 0.12]. A significant positive bias (with participants tending to answer more towards the right of the ground truth) was however observed along the X-axis (0.97cm, [t(244) = 3.72; p = 2e-4; d = 0.24]).

The average precision across participants, measured as the standard deviation of the Euclidean distance between marker and ground truth was found to be 2.11 ± 0.65sd cm across participants. Specifically, this precision decomposed between an average standard deviation of 3.37 ± 1.09sd cm in X and 2.55 ± 0.73sd cm in Y (note that correlations between the two in the experimental data means that these can be expected to be larger than the standard deviation in distance, a larger error in X being compensated by a smaller error in Y and vice-versa).

To analyze the significance of this localization performance, we utilized a Bootstrap test to compare the correlation of the ground truth-response pair locations along X and Y with the correlation obtained from a random association of ground truth and response. Fig.3B shows the correlation coefficient (Pearson's R) between the ground truth and response computed individually in the X and Y axis for bootstrapped couples (sampling with replacement of the couples, in red and green respectively) and permuted couples (sampling with replacement of individual response/ground truth, in blue and yellow respectively). With a significant p-value ($p < 10^{-4}$, the limit of our test), this test demonstrated that the participant were able to use the device to localize the targets in their reaching space well beyond randomness.

B. *Experiment 2 - Identifying Simple Shapes*

To evaluate the performance of the participant during the second experiment, we defined a performance score that scored the overlap between the correct response shape (ground truth) and the participant response shape (see Fig. 4A) :

$$Score = 100 * \frac{T \cap A}{T \cup A} \tag{1}$$

With T and A the ground truth and participant response respectively and $T \cap A$, $T \cup A$, the area of the intersection and union of the ground truth with the response (Fig. 4A) respectively. A score of 0 indicates that the ground truth and response do not overlap at all, while a score of 100 indicates perfect overlap.

The performance of the participants were found to vary heavily with shape (Fig. 4B,D), from an average score of 11 (± 12sd) with the bar to an average score of 28 (± 14sd) with the square. This was understandable because, over all shapes, the bar is the one with the least area, therefore misidentifying the bar for any other shape will lead to a score that cannot exceed 40 (when the bar is contained within the square triangle). Fig. 4B shows the confusion matrix, with the presented shapes in the columns and what they were identified as (and in what %), in the rows. The square shape covered the most surface and was mostly confused with the circle which had similar surface coverage. Similarly the square and circle are symmetric to a 90° rotation which is not the case for the triangle and bar. Therefore the bar and square triangle add a layer of difficulty compared to the square and circle in the sense that their orientation is also important for scoring.

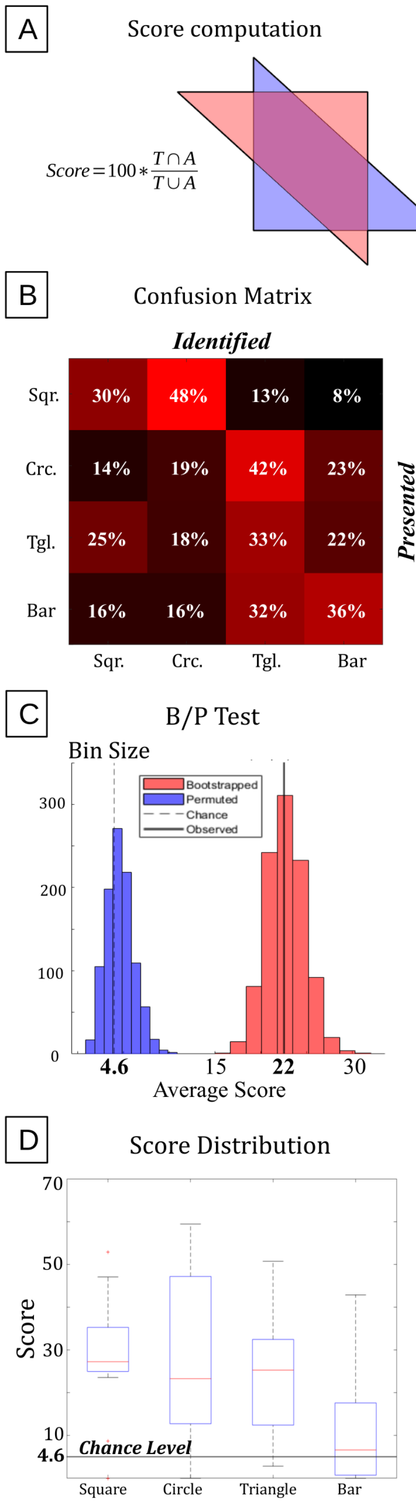

Fig. 4. Performance in Experiment 2. A. The performance score in the task is computed as the area of the intersection of the two shapes (in violet) divided by the area of the union (bold black line), S = 47 for this example. B. The confusion matrix between shows the presented (in column) and identified (in line) shapes. C. The distribution of average error for bootstrapped couples of presented shape / identified shape (Bootstrapped in red) and permuted couples (Permuted in blue), total bin size is 1000. D. The score computed individually for each shape presented during the experiment, a score of 0 indicates that the ground truth and response do not overlap at all, while a score of 100 indicates perfect overlap.

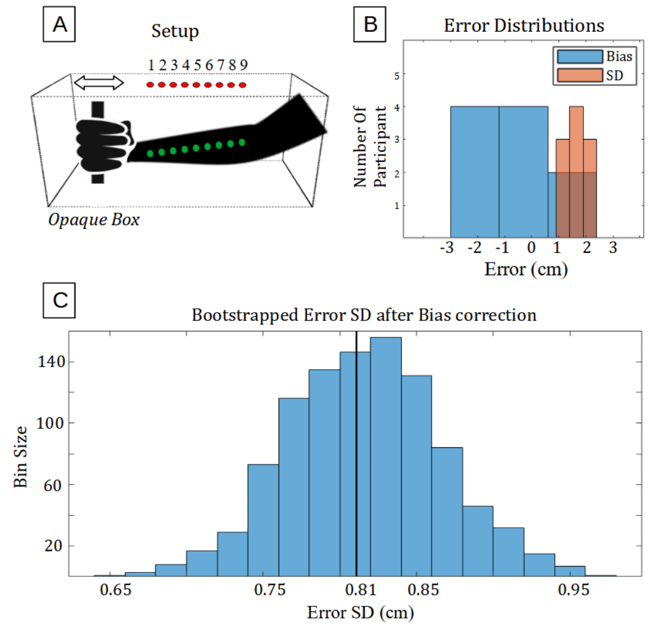

Fig. 5. Performance in Experiment 3. A. The participant were asked to point on the box (red mark) the position closest to the location chosen by the experimenter to apply the tactile stimulus (green mark on the arm). B. The distribution of mean and standard deviation of error exhibited by each participant across all 15 trials, for the mean, the positive axis is oriented from the hand towards the elbow (from left to right in A). C. The distribution of the standard deviation of error exhibited by a thousand bootstrapping of the participants' answers after bias correction. The obtained average standard deviation for the error is 0.81cm.

It is to be noted that the performance score we use here is a very strict measure that decreases quickly with small misses in the localization. To evaluate to which extent the scores we obtained are therefore significant, we decided to compare the participants score with chance level using the same test as in Experiment 1. We performed permutations of the responses and answers, and bootstrapped those couples to estimate the variability of the results (Fig. 4C). Repeating this process 1000 times, we can see that our participants, even with a seemingly low average score of 22 (± 16sd) across the shapes, were performing way beyond chance level ($p < 10^{-3}$, once again the limit of our test) which was around 4.6 with this score measure.

The average score across participant were also significantly different from chance level for each of the 4 shapes; for the square [t(11) = 6.10; p = 1e-4; d = 1.97]; for the circle [t(11) = 4.07; p = 0.02; d = 1.32]; for the triangle [t(11) = 5.31; p = 2e-4; d = 1.75]; for the bar [t(11) = 2.22; p = 0.048; d = 0.88].

C. Experiment 3 - Estimating a position from touch

To evaluate the precision with which participants were able to spatially localize tactile stimulation on their arm, we calculated the distance between the position identified by the participant (response) and the real stimulation by the experimenter (ground truth). The average absolute distance between the response and ground truth was found to be 1.74 ± 1.59sd cm across participants. This was about 61% of the (absolute) error we observed in the X and about 80% of the error we observed in the Y direction in Experiment 1. Overall, most participants (8 of 10) showed a negative bias (towards the elbow) in their estimation of the position but some (2 of 10) showed a positive bias (oriented towards the hand). Figure 5 shows the distribution of bias (A) and standard deviation (B) for all participants. Bootstrapping the answers given by each participant after bias correction (Fig.5C) shows that the participant were able to identify a position from tactile stimulation with a precision of 0.81 ± 0.05sd cm on average. Given that on average, the precision of responses of the participants in Experiment 1 was 2.11 cm across participants. This result suggests that almost 38% of the precision error in Experiment 1 were due to natural inaccuracies in the spatial precision of tactile cues by humans.

IV. Discussion

In this study, we presented a prototype of tactile scanner aiming to enable its users to intuitively detect objects in the vicinity of their forearm. We examined the ability of our participants to employ this prototype to detect and identify objects in their reaching space. The proposed prototype employs capacitive sensors providing non-directional measure of distance across a the user's reaching space. Over two experiments, in which the device was affixed on the participants' forearm, we quantified their performance in terms of the spatial accuracy with which they were able to localize small objects as well as how well they were able to discriminate between simple shapes.

The first experiment showed that the participants could localize the objects using the scanner with an error of 2.88 cm along X and 2.2 cm along Y (Fig. 3A). It is interesting to note that these values are very close, or below, to the size of the individual capacitive cells (3 by 3 cm). In other words, the participants were able to locate the objects with an accuracy below the sensors resolution. This was arguably possible because participants were able to integrate movement related gradients in the vibration feedback to improve the precision of their response. It is also interesting to note that the use of the device yielded unequal performance along the X and Y axis (red and green plots in Fig. 3B) while the distribution at chance level remained the same for both axis (blue and yellow plots in Fig. 3B). This difference in performance therefore, cannot be explained by the higher number of cells available in X (columns, 30 cells) versus in Y (rows, 18 cells). An explanation for this result probably comes from the configuration of the experiment. When the participants faced the setup with his arm extended over the search area (Fig. 2A), the device was oriented roughly along the Y axis. Conversely, it was difficult for our participants to rotate and orient their arm completely along the X axis. Hence, while the Y-axis position may be estimated by feeling the modulation of vibration along their forearm, the participants had to predominantly use arm movements and movement related gradients in vibration to estimate the positions of the objects along X.

Similarly, the positive bias we observed for both the X and Y axis can be arguably be explained by the position of the participant during the experiment. For the Y axis, the positive direction points towards the participant. Therefore, the cell with higher Y coordinate are easier to reach. For the X axis, the positive direction points to the right of the participant. Given that all of them were right handed and therefore wore the device on their right arm, the cell with higher X coordinate were also easier to reach. It is also quite certain that parallax effect played a role in this observed bias seeing the effect it had in the third experiment. Most of the participant exhibited a large negative bias (towards the elbow, Fig. 5B) consistent with a neglect of parallax effect given their point of view (in Fig. 5A the participant view vector come from the top-right). It is however unclear how these two effects might have interacted with each other given the experimental setup.

The second experiment showed that participants were relatively successful in detecting and identifying shapes from the vibratory feedback. While object localization is possible by estimating the vibration gradients, shape detection also requires one to detect edges and invariably remember and integrate gradient information over time. Though, as a whole it may seem that the ability to identify shapes with the device was fairly poor (with performance scores of 30, 19, 33 and 36 for the square, triangle, circle, bar respectively), there are several issues that should be considered here. First, a look at the confusion matrix (Fig. 3B) of their identification in fact shows that the participants were able to identify the object size quite well. The bar, which was smallest of the objects by area, was most of the time identified as the bar (see diagonal of confusion matrix). The square on the other hand, having similar coverage as the circle, is misidentified as a circle in almost 50% of the trials. On the contrary, it was rarely (8%) mistaken for the bar. The fact that the circle was often (42%) misidentified as the triangle also hints that the participants were able to roughly detect the shape edges, the triangle and circle being the only two shapes that have edges non-aligned to the grid. Second, it is to be noted that the shapes the participants were presented were quite small in relation to the capacitive sensors, making a difference in size hard to recognize, and possibly blurring of the exact location of the shape edges. Moreover, participants had no prior training with the setup and had to work without feedback throughout the experiments (ie. we never disclosed the correct response at any point during both experiment) as we preferred not to modify their performance through learning. It has however been shown that training can improve the ability of a participant to recognize simple geometric shape using TVSS [21]. We therefore believe that these results can be also be improved by allowing the participants to adapt to the device if offered feedback on the result. Overall, while the results show that participants are able to identify shapes above chance level using the device, further research is necessary to precisely evaluate this ability and to understand to which extent can it be improved through training. Finally, the device we present here is far from optimal. For example, it is known that different tactile receptors on the skin (Pacinian's corpuscule, Meissner's corpuscule, Ruffini's endings, Merkel's ending and free nerves endings to name a few) have different sensitivity to stimulation frequency as well as having different rates of adaptation to continuous stimulation [12], [17]. In the current implementation, due to the use of vibratory motors, proximity changes lead to correlated modulations of the frequency/intensity of the vibrations. The device in its current form thus involve multiple sensory receptors on the skin in its feedback of proximity information. It is to be expected that different stimulus pattern/intensity would lead to different result and the question of an optimal feedback profile given an application is still an open question [20].

In conclusion, this study examined the potential of a new type of SES device, a "tactile scanner" designed to assist its users in monitoring their reaching space without relying on vision. Given this application, we investigated the use of capacitive sensors to measure the distance of the user's limb to various objects in the reaching space. The ability to modulate the saliency of different surfaces to the device and its user is an interesting aspect of the technology for future research. For example in giving contextualized information in scenarios or to highlight "point of interest" (a lifeline in an emergency) to drastically ease the use of such device.

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