Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

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ABSTRACT

In daily life, we frequently feel for objects without vision using our senses, called Haptics. Much of the research that has been done in this area is focused on single-handed searches, with no agreed-upon conclusion on if two hands are better than one. Here, we asked if there is a clear advantage, disadvantage, or no difference in simultaneous bimanual compared to sequential unimanual search. Participants felt for a unique target item that differed in length or texture amongst uniformed distractors with their left hand only, right hand only, and with both hands simultaneously. Additionally, we examined how performance might vary when the distinguishing feature of the unique target was the same or different between the hands. Simultaneous bimanual search showed significantly more efficient search than the sequential unimanual search. Surprisingly, there was no appreciable difference between performance when searching for targets with the same and different features. This suggests that the advantage of searching bimanually is not due to sensory redundancy or perceptual advantages from shared features. Future research will investigate the role that action coupling might play in the bimanual search advantage. These findings can apply to developments in robotics, prosthetics, and rehabilitation processes. Additionally, they can support our understanding of attentional deployment in understudied modalities like haptics.

KEYWORDS: Haptics, Haptic Search, Bimanual, Attention

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Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

INTRODUCTION

Touch is an important ability that allows us to interact with the world and those around us. We often use touch to perform tasks such as looking through one's bag to find keys or feeling for loose change.. Harlow and colleagues' (1958) classic attachment experiment on monkeys demonstrated that the sense of touch dictates their behavior, particularly their attachment-related behaviors, highlighting the fundamental importance of touch on emotional connection and practical tasks. Similarly, humans rely on touch to complete practical tasks, typically using our hands to explore objects and interact with our environment.

Haptic search, a key part of the cognitive psychology discipline, is a process that relies on touch sensation. It is crucial for tasks where vision is limited or absent, such as retrieving items from a cluttered bag, searching under furniture, or reading braille. Kapper and Bergmann Tiest (2013) have set a framework for haptics and explained how individuals search for objects and detect features associated with them. They have uncovered that haptics involve tactile cues and proprioceptive kinematic cues. Studying haptic search helps deepen our understanding of how we process sensory information through touch. It also has many vital integrations in fields from medicine to robotics, yet research considering the contribution of both hands remains limited.

Plaisier and colleagues (2008) used a single-hand search task that demonstrated pop-out and search asymmetry, both perceptual phenomenons related to attention. Participants used only their dominant hand to perform quick sweeps over a search field that contained a textured sandpaper surface that varied in roughness. These findings demonstrate that haptic attention is captured more readily by the presence of a feature, than its absence. Lederman and Klatzky's (1997) study gives further insight into how objects' features give rise to search strategy selection. These studies on single-hand search provided valuable insights into the mechanics of attentional deployment in single-hand exploration. However, the level of integration of this information and to what degree attention can be shared between the hands is not well understood.

Overvliet and colleagues (2008) provided foundational evidence for bimanual haptics experiments that utilize both hands. Their experiment instructed participants to locate a specified target item among uniform distractor items without their vision. The search field consisted of a grid of cubes fixed to the table. The study showed that searching with a single finger was slower than searching with one hand, and using two hands was the most efficient. This demonstrated that more sensory receptors (by using more fingers or hands) led to quicker search, suggesting optimal sensory integration.

In contrast to Overvliet and colleagues (2008), we used a free-range haptic search task, which allowed objects to move freely instead of being fixed in one position. This approach allows for simulation of how objects are searched for in everyday life with unpredictable orientation (Sturgill & Rosenbaum, 2025). Additionally, it allows us to confirm that this effect was not due to exploitation of the fixed array.

Other researchers have investigated if observed bimanual advantages are due to optimal sensory integration between the two hands (Squeri et al., 2012). The authors suggest that if the hands are represented as separate perceptual systems, then one would expect higher perceptual accuracy. However, Squeri and colleagues (2012) discovered that when participants identified the curvature of objects with both hands, the brain did not always combine input optimally. Instead, participants relied more heavily on one hand's input, a phenomenon known as sensory selection. The lack of consistent integration indicates that the bimanual performance advantage may result from motor coordination and spatial labor distribution rather than increased sensitivity to input. This begs the question of if Overvliet and colleagues' (2008) results were due to perceptual sensitivity or spatial labor distribution. Our study was designed to control for the labor distribution, while contributing to the literature on bimanual haptic processing.

HYPOTHESIS AND PREDICTIONS

We investigated if using two hands provides a clear advantage, disadvantage, or no difference in search performance compared to using a single hand. Previous research has shown mixed results for bimanual performance compared to unimanual, citing various mechanisms like multisensory integration and division of labor (Jones & Henriques et al., 2010). We controlled for the division of labor between the unimanual and bimanual conditions while using an ecological laboratory task (Sturgill & Rosenbaum, 2025). Additionally, we wanted to test the multisensory integration account by varying the similarity of the judgments being made between the hands. Our questions were both exploratory and theoretical: Would we find clear evidence of a difference between bimanual and unimanual search using a different task? If the previous bimanual advantage was due to a similar mechanism, such as multisensory integration between the hands, then by varying the similarity of the judgments for items being felt, the subsequent performance should vary as well. We predicted that using two hands simultaneously would result in higher efficiency than searching with one hand and then the other sequentially. We also asked if search performance would significantly improve for items requiring the same judgments compared to items requiring different judgments about the relationship between the target and distractors.

If searching simultaneously with both hands is done sequentially, then no difference should be observed between the summed single-hand searches and the observed both-hand searches. Additionally, if using both hands simultaneously places a greater demand on the system, then both-hand searches should be less efficient than the sum of the sequentially performed single-hand searches. Lastly, if bimanual search is sensitive to the similarity of the features of the items being felt by the hands, then searches for targets with the same features should prove more efficient than when the targets do not share the same features.

METHODS

The goal was to measure how quickly and accurately participants identified the unique target within a set of repeated trials. We recorded the time taken to select the odd object and the accuracy of the selection. Using a free-range search task, participants were asked to identify an object that differed from the rest by using touch alone. No visual cues or previews were provided to participants, unlike in the original experiment that utilized this task. The unique target item differed from the distractor items by either texture or length. The length feature was chosen as it is well documented for its systematic psychophysical properties (Stevens & Stone, 1950). Texture differences were equally well studied, as mentioned previously, and allow for greater control of the experiment apparatus.

Experimental Setup

Participants searched in two 6x6-inch plastic containers secured to the table with Velcro straps, which were positioned for left- and right-hand placement. A black poster board was placed above the containers to occlude participants' vision of the search field. Each container held seven pieces, six uniform distractor items, and one target, which was different either by length or texture. All search items were made from PEX pipes, with the diameter kept consistent for distractors and targets (0.5-inch), but varying in length. The distractor items and texture-based targets measured 1.5 inches in length, and the length-based target items measured 1.0 inches in length. The texture-based target differed from the distractors by having small 1mm holes spaced every 3 mm along its length and at every 90 degrees about its circumference. A metal touchpad was positioned between the two containers, which was used to record the duration of the search time for each trial. Participants wore a Velcro ankle strap connected to a Makey-Makey ® device that detected their touch in MATLAB. The Makey-Makey® enabled participants' touch to be captured and translated into a format that the software could interpret and process (Sturgill & Rosenbaum, 2025).

Procedure

Participants completed an Informed Consent Form outlining the study's purpose, procedures, risks, and rights. This study was approved by the Human Research Review Board (HRRB) at the University of California, Riverside. A background survey regarding demographics and hand dominance was administered.

Participants sat centered in front of the table to easily access each search field. They searched for one target item among six distractors using only their sense of touch. Seventy-two trials were divided into nine blocks with eight trials each. The nine blocks comprised three right-hand-only conditions, three left-hand-only conditions, and three both-hand conditions. The order of the blocks was randomized; therefore, the hand condition the participant started with was varied. In each of the blocks, the object feature varied among the trials.

Across all trials, participants searched in the right container with their right hand only and the left container with their left hand only. In some subsets of trials items were present in both containers and participants searched with both hands simultaneously. In other trials, participants found items in only one container and searched only that container. If items were present, then that container had a target to be found. This ensured that the only difference across both hands and single hand searches was that both hand searches were performed simultaneously, while single hand searches were done sequentially. At the beginning of each block, participants were told which container(s) to expect objects for each trial and thus how many targets they would need to find.

Once the participant had found the target in the container, they grabbed and held the target item(s) in their hand(s) and tapped the touchpad to indicate the end of the search. They then presented the item(s) under the poster board for the experimenter to see, and the experimenter provided accuracy feedback by stating "correct" or "incorrect." This was recorded by the experimenter using the keyboard with a 1 or 0, respectively. Next, the participant placed the target item(s) in their respective container(s) and removed their hands from the search area. This concluded a trial, and this process was repeated until 72 trials were completed.

Participants/Data

The study was conducted during the Fall 2024 and Winter 2025 quarters at the University of California, Riverside. Fifty participants were recruited from the Psychology Research Participation System (SONA) subject pool and were compensated with course credit. Thirteen participants were removed from the final data set for having incomplete data sets. Therefore, the final data consisted of 37 participants: 67.9% females, 32.1% males, 2.7% left-hand dominant, and 97.3% right-hand dominant. The final data cleaning process involved imputed mean search times per participant per condition. Search times that were longer than 3 standard deviations above the mean search time for that participant in a specific condition were replaced with the participant's mean. This replaced only the top 0.1% of the longest search times per subject and thus less than 3.7% of all data.

Figure 1: Experimental Apparatus

Note: Panel A shows the experiment apparatus as a whole. The two containers are centrally located within the black frame that holds the poster board (not shown). On the left side of the image is the anklet (a black band with red strap and wire). To the right of the poster board frame are the experimenter's keyboard and the cups, which contain multiple sets of the two conditions. Panel B shows the two conditions (Texture left and Length right).

Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

RESULTS

Participants performed haptic search without vision to determine the target item among distractors. We had two questions: first, if utilizing both hands together provided better performance in accuracy and mean search time, compared to the summed sequential single-hand searches. Second, if performance varied when both hands searched for targets distinguished by different features, compared to when searching for targets with the same feature. Our study examined if bimanual search times would differ from the summed search times of the left-hand and right-hand, which served as a baseline measure. The study used repeated-measures Analysis of Variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) test to assess performance differences between conditions. The research findings are illustrated in three figures, displaying accuracy, mean search time, and efficiency.

The ANOVA supported an appreciable difference, $F(7,252)=2.52$, $p = 0.016$, $\eta^2= 0.07$ between our conditions. Although there was a visual difference between searching for length-based items and texture-based items for single hand searches, the HSD test revealed that there was not an appreciable difference in the proportion of correct responses. There was no statistically significant difference between "left length" and "right length" $t(7)=0.019$, $p = 0.994$. For "left length" and "left texture" in single hand search, there was no significant difference, $t(7)=0.096$, $p=0.096$. This remains the same for "right length" and "right texture", $t(7)=0.102$, $p=0.059$. As for the difference between using a single hand and both hands, the accuracy when searching with one hand was not comparable to that when using both hands, indicated by comparing "left length, right texture" to "right length," $t(7)=-0.081$, $p=0.230$. All pairwise comparisons for the eight groups had a p-value of 0.059 or greater.

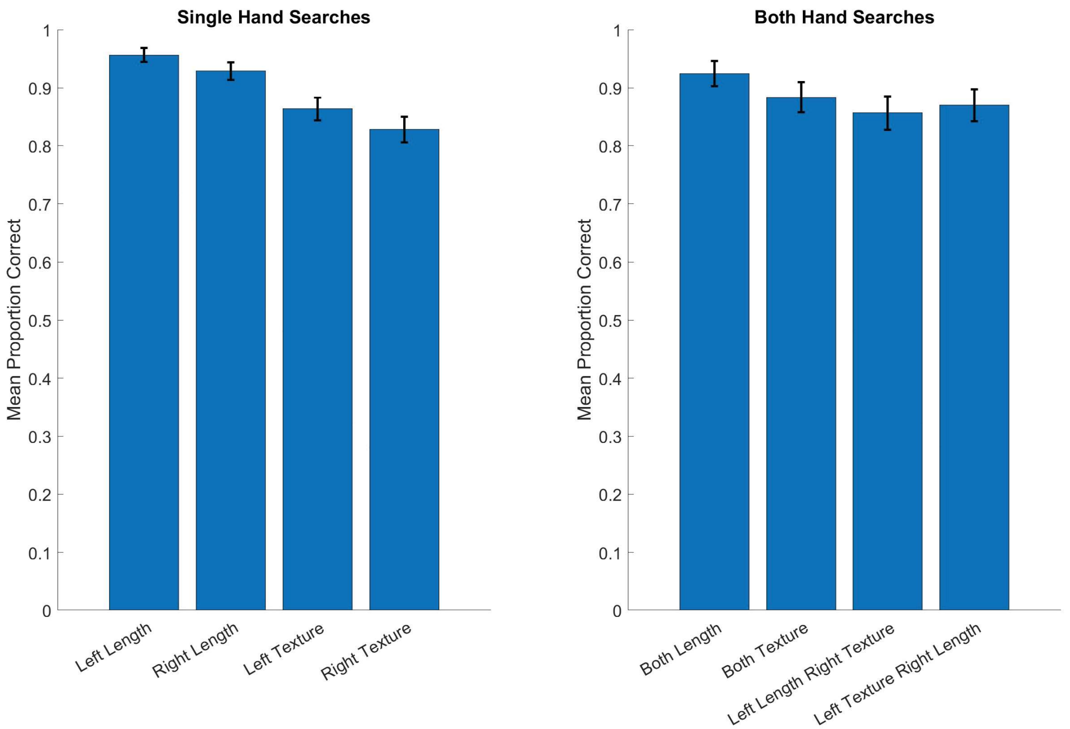

Figure 2: Mean Proportion Correct by Condition Type

Note: Mean Proportion correct (+/- 1 SE) for each of the eight hand conditions tested. The left graph shows the results for single-hand searches paired with length and texture targets. The right graph shows the results for both-hand search conditions, where both hands had the same target or different targets.

Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

Figure 3 illustrates the mean search time for single, both hands, and the sum of single-hand search trials, depending on the target feature (length or texture) when the hands were searching for the same or different features. In Figure 3A, "Single Hand Search" shows the average search time when participants used only the left or right hand to search for a length or texture target. All four conditions (Left Length, Right Length, Left Texture, Right Texture) resulted in similar mean search times, ranging from around 18 to 21 seconds. This suggests that single-hand search times were consistent, regardless of which hand was used or what feature was being searched for, supported by an average mean search difference of 0.85 seconds, and p-values all above 1.000 across the compared conditions.

In Figure 3B, "Both Hand Search" shows the average search times when both hands were used together to search for either the same feature (Both Length, Both Texture) or different features across hands (Left Length + Right Texture, Left Texture + Right Length). All bimanual conditions resulted in similar times (around 30 seconds), with no significant difference between same-feature and different-feature searches, as observed through an average mean search difference of 9.5 seconds, and p-values all above 1.000 across the compared conditions.

In Figure 3C, "Sum of Single Compared to Both When Same Targets" compares the sum of the individual single-hand search times (gold bars) to the both-hand search time (blue bars) when both hands were searching for the same feature. In both cases (Length and Texture), the sum of the single-hand times is noticeably higher than the both-hand search times.

In Figure 3D, "Sum of Single Compared to Both When Different Targets." This graph presents the same type of comparison as the top left panel, but when each hand searches for a different feature. Again, the blue bars (both

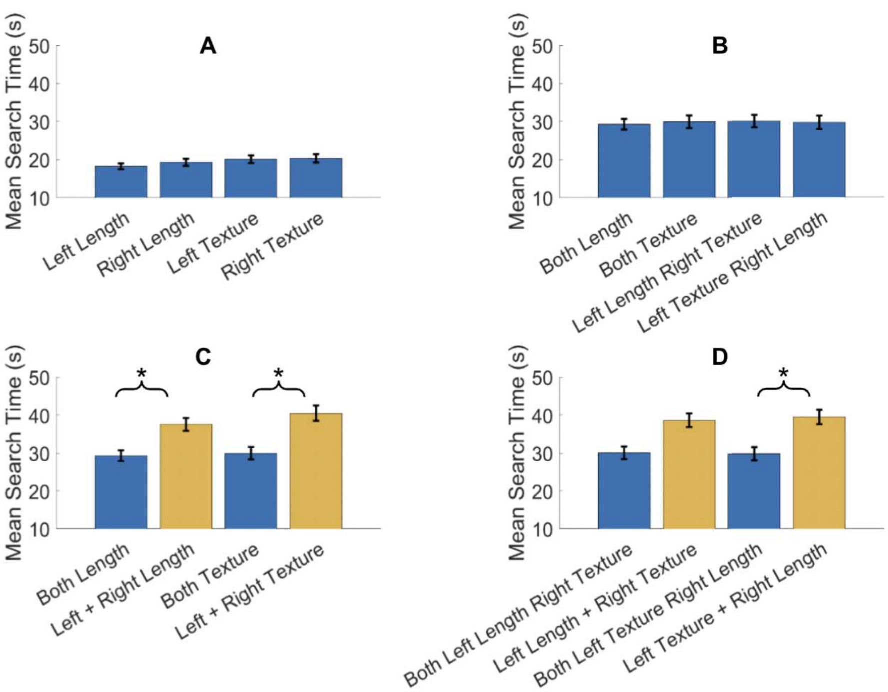

Figure 3: Mean Search Time by Condition Type

Note. Mean search time in seconds (±1 SE) for the eight hand conditions. The top left panel (A) is from single-hand search trials. The top right panel (B) is from both-hand search trials. The bottom left panel (C) is the mean search time when the same targets are used, while the bottom right (D) depicts conditions when targets were different between the hands. Blue bars show observed data. The gold bars are the summed single-handed times from the top left panel. The brackets and the stars depict the magnitude of significance, with one star representing a p-value between 0.05 and 0.01.

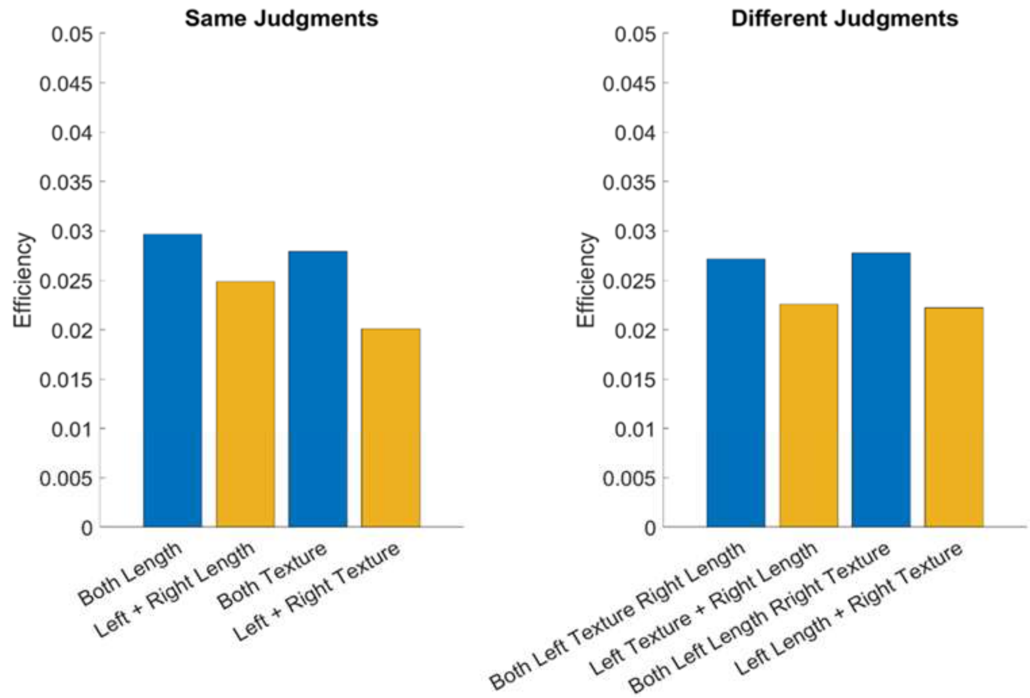

Figure 4: Efficiency by Condition Type

Note. Average Efficiency for Both Hand Conditions. Blue bars represent hand efficiency, and gold bars represent the hypothetical efficiency of individual hands summed together.

hands searching) show faster performance compared to the gold bars (sum of single-hand searches), indicating that even when searching for different features, using both hands together reduced the mean search time.

These patterns in Figure 3 were confirmed through statistical testing. A repeated measures ANOVA detected a statistically significant difference in mean search times between the conditions ($F(7, 252) = 12.78$, $p<0.001$, $\eta^2 = 0.26$), indicating that at least a subset of the search conditions was significantly different from each other. Pairwise comparisons between conditions were conducted using Tukey's (HSD) post hoc t-tests.

When participants used both hands to search for identical features, summed single-hand search times were longer than the observed both-hand conditions. That is, the mean search time in the summed condition "Left + Right Length" was greater than in "Both Length," $t(252) = 3.41, p = 0.031$, with a 95% CI [3.21, 11.87]. Similarly, "Left + Right Texture" took longer than "Both Texture," $t(252) = 3.35, p = 0.050,$ *d = 95% CI [4.25, 16.25]*. This supports the finding that performance when searching with both hands simultaneously was quicker than the sum of the two sequential searches, when the target features were identical.

What about the cases where both hands were feeling different target features? The "Left Texture + Right Length" condition took longer than both-hands. Both Left Texture, Right Length" conditions with those same features (Left Texture + Right Length), $t(252) = 3.33, p = 0.037,$ *95% CI [3.76, 14.50]*. However, when comparing the opposite conditions "Left Length + Right Texture" and "Both Left Length, Right Texture", the results failed to reach significance, $t(252)=2.82, p=0.121,$ *95% CI [2.53, 14.05]*. These results show that in three of the four comparisons we tested here, simultaneous bimanual search was appreciably quicker than forced sequential search.

Figure 4 compares the average efficiency across the same and different judgments conditions paired with the conditions where bimanual search and forced sequential search were performed, the conditions that directly address our primary questions. This measure of efficiency was adopted

Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

from Sturgill and Rosenbaum's (2025) work, where they presented a universal composite measure of efficiency. This measure uses the ratio of observed proportion correct to the expected proportion correct in the numerator and 1+ the average observed time to complete the task in the denominator. Their measure constrains efficiency between 0 and 1, which is reflected in the y-axis. For more details, see Sturgill and Rosenbaum (2025). In our experiment, the expected proportion correct was 0.14 or $1/7^{th}$ in every trial, as the number of distractors was not varied.

The left panel of Figure 4 shows the efficiency scores for conditions where both hands felt for targets that were unique based on the same feature (same judgments). As seen in the panel, the efficiency was higher for the simultaneous bimanual searches (blue bars) than for the summed sequential unimanual searches (gold bars).

Similarly, in the right panel of Figure 4, the observed efficiency was greater for simultaneous bimanual searches compared to sequential unimanual searches. The right panel shows the efficiency scores for conditions where both hands felt for different features, where one hand searched for length and the other hand searched for texture. These convergent results show that, regardless of the similarity in the judgments being made between the hands, simultaneous bimanual search was more efficient. Average efficiency results emphasize that two hands were faster in search times and more effective, which was achieved without affecting the accuracy of the search results. Overall, Figure 4 demonstrated that the simultaneous use of both hands is more efficient than sequential individual hand search when feeling for the same or different targets.

DISCUSSION

Our experiment was designed to investigate haptic search without vision and to understand the difference in performance between bimanual and unimanual search. Our study addressed if two hands would result in higher efficiency and how the search performance differs when searching for items of the same feature in contrast to items that are different; with one texture- and one length-based target. Our hypothesis proposed that performance would improve with the use of two hands over one and searching for items of the same feature would be much quicker. We concluded that the accuracy levels remained consistent across all conditions, between the number of hands used and the varying features of length and texture (Figure 2). Furthermore, the results established that bimanual search had a faster search time than the sum of the individual hands, which verified our hypothesis (Figure 3). When using accuracy and search times to calculate efficiency, two hands were more efficient than the sum of individual hands (Figure 4). Overall, our results showed that even when controlling the work being done by the hands and the similarity of the objects between the hands, the simultaneous use of two hands was more efficient than the sequential use of the individual hands.

Limitations and Further Directions

In our study, all items were standardized PEX pipes to test features one at a time and minimize potential confounding variables that arise from using objects with varying characteristics. However, this approach contrasts with real-world scenarios, where targets involve diverse shapes, sizes, and textures. Although we tried to be as ecological as possible, future research might benefit from using more naturalistic objects to better reflect real-world conditions. Furthermore, our participants consisted only of UCR undergraduate students, so the data may not apply to other age and demographic groups. Another limitation of our study was that participants' hands were always symmetrical in all conditions, making it unclear if this may have influenced performance. This limitation will be addressed in future research by exploring variations in hand positioning.

Future research will investigate how the location of the search containers affects bimanual performance. The symmetry of the containers in our experiment was consistent throughout all trials, but testing different locations where either the left, right, or both hands are closer or farther from the subject could shed light on if there is a bimanual coupling involved. Action coupling, where coordinated movements between hands are naturally linked, can either facilitate a positive effect or constrain actions when searching for items. Examining these factors will give more insight into the underlying mechanisms of bimanual search and how performance is affected.

Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

CONCLUSION

Bimanual haptic search demonstrated significant efficiency and performance benefits compared to single-hand search. In general, the human brain is effective at processing different sensory inputs simultaneously (Stein, Stanford, & Rowland, 2014); however, bimanual search was substantially more effective due to the use of two hands, which supports the overarching points that bimanual exploration provides many benefits. Therefore, these findings highlight the importance of bimanual exploration and its use in everyday life to identify various targets. Haptic search is a diverse field, with implications ranging from prosthetics to robotics. In prosthetics, haptic search can lead to better tactile sensors and give insights into how humans optimize touch to interact with their environment efficiently. Similarly, haptic search can allow robots to use tactile exploration in simple tasks, such as distinguishing objects in clustered environments by using touch alone. It is important to acknowledge that limited research has been conducted so far in haptic search, which emphasizes the need for further investigation to understand other underlying processes.

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Beyond One Hand: Exploring Underlying Mechanisms of Bimanual Haptic Search

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