Title

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Exploring the World by Touch: Guidance in Bimanual Haptic Search

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ABSTRACT

While visual attention has been extensively studied, haptic attention has remained relatively unexplored. Haptic attention is an integral facet of everyday life, often arising in everyday activities like feeling for a pencil in a backpack or searching for keys in one's pockets. We sought to understand how proprioception—our body's position in a three-dimensional space—and the features of an object (such as variation in length or diameter) contribute to the efficiency of bimanual (the use of two hands) haptic search in an unrestrained environment. We hypothesized that the physical properties of an object, along with the areas in which we search for something—our frame of reference—affect search efficiency, which we quantified via search times. Our study required participants to search for a target item among a set of distractor items without the use of vision, either in a single container with hands coupled or in separate containers with hands separated. We found that bimanual search in one container was not reliably different from bimanual search in two containers. We also found that there was an additive effect of diameter and length discrimination on search efficiency. This effect pertained to length searches always taking longer than diameter searches within the conditions.

KEYWORDS: haptic search, bimanual search, frames of reference, proprioception, attention, features

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David A. Rosenbaum, Ph.D. is a Distinguished Professor in the Psychology Department (in the Cognition and Cognitive Neuroscience area). He recently was honored by being invited to publish Cognitive Control of Action: Selected Works of David A. Rosenbaum in the World Library of Psychologists Series (Routledge Psychology Press, 2024), being one of only 24 psychologists in all areas of psychology to publish a collected-works volume since the series began in 2013.

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INTRODUCTION

Imagine texting a friend while reaching into your pocket to grab your car keys. Or, imagine driving while trying to grab your backpack in the back seat. In both cases, you search with your hand without the benefit of vision. Vision is a complex, important, and advanced human sense that has been extensively studied due to it being a primary driver in our daily lives (Gerrig & Zimbardo, 2008). Conversely, touch, and more specifically unconstrained haptic search, has been less studied (Rosenbaum, 2017).

There is precedence for research on haptic search, however. In a study that is particularly relevant to our present research, Overvliet, Smeets, and Brenner (2018) created a bimanual search experiment exploring the differences of finger use in three conditions: one finger, multiple fingers of one hand, and free use of both hands. They aimed to find out how quickly a target could be found while vision was obscured via an eye mask. Participants were asked to identify a target item—a cylinder, bar, or a rotated cube—placed within a set of distractor cubes that were fixed in a grid. The authors found that search was quickest for the cylinder, as it was the item most different from the distracting cubes. Additionally, Overvliet et al. (2018) found that searching with both hands was quicker than searching with a single hand in all target conditions and that one-finger search was slowest of all in all conditions. The authors concluded that searching with separated hands afforded a division of labor, where each hand could divide the objects amongst them and access each object simultaneously.

Overvliet et al. (2018) creates a great foundation for understanding haptic search, but we wondered whether the main result would remain in a more natural setting. In real life, objects to be felt do not sit affixed to boards in nicely gridded patterns. Instead, they may be piled up or scattered to occupy separate areas. We sought to address this idea with the creation of a more naturalistic task in our experiment. In addition to the idea of naturalism of the earlier work and its reliance on a grid, another feature of the study by Overvliet et al. (2018) interested us. It was unclear whether the spaces in which the two hands did their searching were functionally shared or separate. Other foundational literature speaks to this issue. Squeri and colleagues (2010) designed a bimanual haptic experiment using coupled and uncoupled hands as their conditions. The authors showed, by relying on Bayesian analysis—a statistical approach integrating prior knowledge with observed data, enabling researchers to address uncertainties and present probabilistic inferences—that a shared frame of reference aided haptic search. In their experiment, which also obscured vision, participants indicated which of two pathways felt more curved via touch. Higher levels of accuracy could be achieved when the hands were coupled—or when the two pathways to be felt occupied a space that could be explored by both hands. In this case, a shared frame of reference could improve haptic perception of curvature.

In retrospect, the two studies reviewed above can be said to have had opposing results, as one study supports the greater efficiency of separated hands in search tasks while the other favors coupled hands. The first study may suggest that haptic identification benefitted from separated hands due to the division of labor while the second study may suggest that haptic identification was enhanced by coupled hands due to the opportunity for redundancy. Here we seek to test just that, using a naturalistic haptic search task which we referred to as "free-range haptic search."

In addition to testing frames of reference and perceptual redundancy, we sought also to test the physical features of an object and their influence on search times. Our inspiration came from classic work on visual search by Treisman and Gormican (1986). Through a series of experiments, the authors recorded the time it took for participants to indicate whether visual targets were present among visual distractors. The authors found that larger targets among smaller distractors were found quicker than smaller targets among larger distractors.

Our study continues the research completed by Sturgill and Rosenbaum (in review) which pursued an analogous outcome in touch, but within a more natural haptic-search environment. They had participants hunt for a 1-inch long plastic pipe among a variable number of distractor pipes, all of which were shorter or longer than the target by the same length difference. The diameters of the pipes were the same in all conditions. The primary discovery revealed that the search time for a consistent 1-inch target varied based on its size relative to other objects. This relationship between target and distractor items, referred to as the relative size ratio from here on,was quantified using the formula: (*max*_length - *min*_length)/*min*_length). The data was effectively represented by a power function, illustrating the dependency of search times on the relative size ratios between targets and distractors. Notice that, for this function, as min_length increases, the ratio gets smaller, so as in Treisman and Gormican (1986), it took less time to find the target when it was larger than the distractor (when the target had max_ length). This reduction of the search time was larger with the greater the difference between max_length and min_length.

HYPOTHESES AND PREDICTIONS

In the present study, we extended the earlier work of Sturgill and Rosenbaum (in review) in two ways. One was to add another dimension to the search difference—including pipe diameter to the existing length searches. The other was to use two-hand search in two different areas (separate frames of reference) or together in one area (shared frames of reference).

Our first hypothesis concerned bimanual haptic search and, more specifically, whether searching in one space with two hands, or searching in two spaces with two hands, differed in terms of search efficiency. If haptic search benefits from a shared frame of reference and from redundant tactile sampling of any given object, then search should be most efficient in the single search space in accordance with Squeri et al. (2012); in our experiment, search area was the Tupperware® container. On the other hand, if haptic search benefits from division of labor, then distinct search spaces should be most efficient as seen with Smeets & Brenner (2008).

Our second hypothesis concerned target features and their relation to distractors. We sought to test this relation by controlling for the relative size ratio from previous research which best predicted search times. In addition, we varied the feature—length or diameter—that distinguished the target. If search is guided by the relative difference between the target and distractor, then there should be no difference in search efficiency between our conditions as the ratio was held constant. However, if search is guided differently depending on the feature, then the data should show varying search times depending on the condition.

METHOD

Materials and Apparatus

For the experimental setup, all search items were found inside the plastic Tupperware® containers. Depending on the condition, participants either conducted searches with their hands divided between two containers, each measuring 6x6 inches, or they did a combined search in one container, measuring 12x6 inches. As it was important to ensure participants could not see the search materials, a black poster board was placed above the search area.

In the container(s), search items consisted of PEX pipes, which are primarily used for plumbing purposes and easily purchased at any local hardware store. In every condition, there was 1 target item and 5 distractor items which varied from the target in either length or diameter—the target item was either shorter/longer than the distractor items or the target item was either wider/thinner than the distractor items, never both (see Figure 1, right panel). Lengths included either 0.50 inches, 0.75 inches, 1 inch, or 1.50 inches. Diameters included either 0.50 inches or 0.75 inches. To ensure that the relative size ratio was controlled and kept constant in the experiment, the 0.5-inch and 0.75-inch items were always tested together, and the 1-inch and 1.5-inch items were always tested together.

Before commencing and immediately after concluding each search task, participants utilized a 3" x 4" metal touchpad to record individual trial search times, shown in Figure 2 (top panel). The touchpad was connected to a Makey-Makey® device, used by children for educational and recreational purposes. Makey-Makey® allows for any organic material to interface with a computer where contact is registered as a key press of one's choosing. Participants wore a velcro anklet which connected the Makey-Makey® device and to the metal touchpad (see Figure 2, top panel) which allowed them to interface with the MATLAB (version R.2023b) data collection program (available upon request). The program indicated whether the touchpad registered any contact during the experiment and provided guidance, such as "Participant, reach for target and touch contact when done," via a monitor facing the participant. The guidance was given as the participant advanced through the program.

Figure 1: Search Conditions

Note. The target items are indicated in red while the distractor items are blue. The left panel image shows an example of a condition varying by length, while the diameter is kept constant. The right panel image displays the 16 different conditions administered in the experiment.

Figure 2: Experimental Apparatus

Note. In the top panel image, the two containers are shown as an example for the separate frames of reference search; in the shared frame of reference search, the two containers are removed, and one container is placed on top of the velcro between the two containers. The touchpad's positioning is vital for the participant, as they tap it on the way to search in the containers. The black anklet is shown on the middle left of the table. The bottom image represents the participants' view as they enter the room. Conditions are withheld in the red cups, showing labels of their appropriate condition number (1-16). Each condition has two cups, for simpler execution in the two-container condition. The keyboard is placed at an easily accessible location for the experimenter. Participants' vision is impeded by a black poster board.

Design and Procedure

Signed consent was obtained before beginning the experiment. Subjects sat comfortably in a chair, with the sagittal midline of the body aligned with the center of the experimental setup. The experimenter began by reading the instructions, followed by the participant being asked to repeat their version of the instructions to ensure understanding. Within those instructions, it was emphasized to search for the target item as quickly and accurately as possible.

Before commencing, the experimenter established if the participant was odd-numbered or even-numbered; if the participant was odd-numbered, the experiment began with one container and swapped from one to two containers at the halfway point—after 16 trials. Even numbered participants followed the opposite procedure.

After the appropriate container and conditions were placed by the experimenter, participants used their knowledge of the instructions to begin searching by tapping the metal touchpad on their way to the Tupperware® container. In one container conditions with 6 PEX pipes, both hands would be used for search—the shared frame of reference condition. On the contrary, in two container conditions, the right hand would search in the right container consisting of 3 PEX pipes while the left hand would search in the left container consisting of the other 3 PEX pipes—the division of labor condition (see Figure 2).

After locating what was thought to be the target item, the participant removed it from the container and touched the metal touchpad again. The participant presented the target item underneath the posterboard and the experimenter delivered verbal accuracy feedback in the form of "correct" or "incorrect." The target item was red in color to help the experimenter easily distinguish it from the blue distractor items. Following feedback delivery, the participant placed the target item back into the container from which it was initially removed. The conditions were then changed by the experimenter while the participant had a brief break. This process was repeated throughout the experiment until the completion of all 32 trials. Conditions were randomized per participant. Debriefing was performed accordingly and all questions were answered.

Participants

We tested 47 UCR undergraduate students who were recruited through the Psychology Research Participation System (SONA) for course credit in the Winter 2022, Spring 2022, and Fall 2023 quarters. The study was IRB-approved. According to the Office of Diversity and Equity at UCR (Fall enrollment at a glance, 2023), the undergraduate population consisted of 33% Asian, 23.3% Hispanic, 21.6% White, 22.1% other. Gender breakdowns included 52.8% women, 44% men, and 3.2% other.

Search time data were imputed if they were less than .5 seconds, which we deemed a sign the participant double tapped the contact to start their timer and immediately stopped it. We also imputed the median time for data where the search was too long or greater than three standard deviations from the participants' mean search time. Lastly, a small amount of data was excluded due to errors in the administration of the experiment and/or equipment malfunction. Our final usable data was obtained from 45 participants which exceeded our a-priori power analysis (conducted in G*Power version 3.9.1.7), where a total sample size of 40 participants was required to compare interactions between two groups across 8 conditions with 2 measures each, to show an effect size f of 0.22 or greater.

RESULTS

Container Comparison

Figure 3 provides a comprehensive summary of the experimental findings by consolidating all of the collected data into a single omnibus figure. Inspired by Brenner and Smeets (2022), the utilization of this omnibus figure effectively combines accuracy and search times into one measure, providing a comprehensive view of the overall impact of container variation. This figure integrates accuracy—measured in proportion correct—and mean search times to generate a central metric of efficiency. This value was devised by dividing the average search times across all searches within each container condition by the proportion of correct trials (the number of correct trials divided by total trials). A two-sample t-test on the average time for correct responses revealed that the difference in the mean of the two groups was not significantly different: $t(90) = 0.765, p = 0.446$, 95% CI [-2.22, 5.00].

Volume Variations on Search Times

To examine the impact of target features on search times, an 8x2 analysis of variance (a repeated measures ANOVA) was conducted on the search time data for each of the eight target volumes and the two dimensions that distinguished the target from the distractors—length or diameter—in Figure 4. The results showed a significant main effect for the dimension that distinguished the target from the distractors, with mean search times differing between searching for length and searching for diameter, $F(1,736) = 31.31, p < .001, \eta^2 = .044$. However, the interaction between the target volume and the distinguishing dimension, and the main effect for the volume of the target were not appreciable, $F(7,736) = 1.06, p = .386$, and $F(7,736) = 1.86, p = .073$, respectively. The results support that the relative size ratio between the target and distractors alone was not sufficient to predict search times.

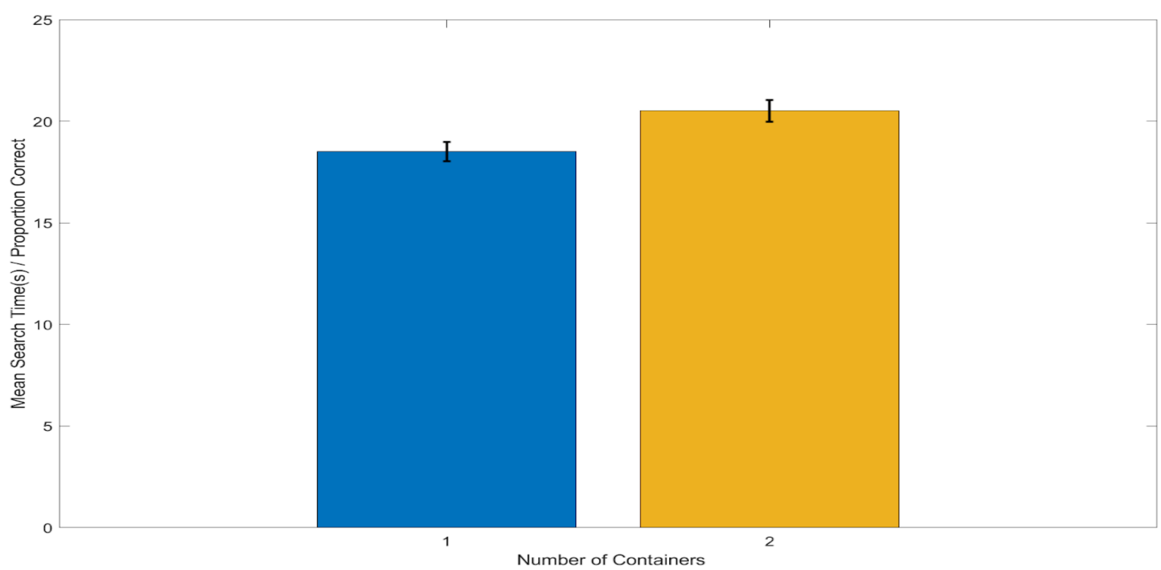

Figure 3: Grand Mean Search Times.

Note. The time for correct responses when the hands worked in a single container (blue) and when the hands worked in separate containers (gold). The time for correct response is the mean search time divided by the proportion of correct responses. The error bars represent the standard error of the mean of search times.

Exploring the World by Touch: Guidance in Bimanual Haptic Search

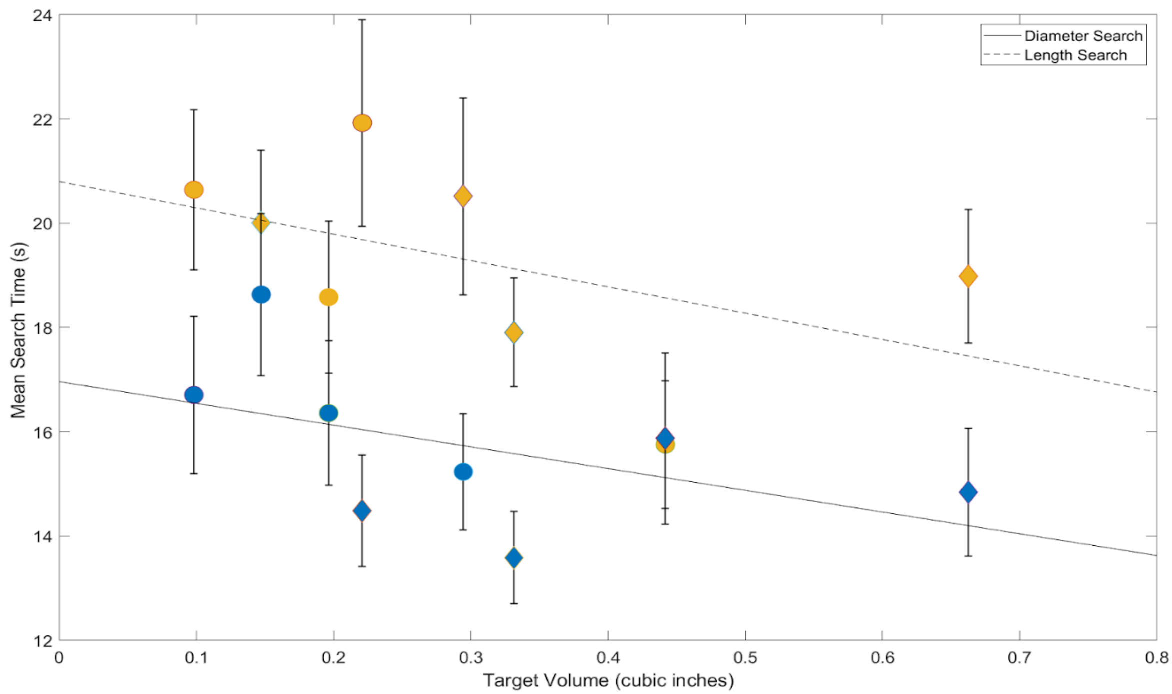

Figure 4: Mean Search Times as a Function of Volume

Note. Mean search times (±1SE) as a function of the volume of the target object when the dimension that distinguishes the target is its diameter (Blue) or length (Gold). The line represents the best-fitting regression for each of the two search types, length and diameter. The marker shape distinguishes search when the target was the smallest object (Circles) and when the target was the largest object (Diamonds).

DISCUSSION

Our study sought to shed more light on the relatively unexplored field of vision independent haptic search. We aimed to better understand some of the underlying mechanisms at play when it came to influencing the efficiency of bimanual search. We specifically focused on how the magnitude—represented by the overall volume of the targets—along with frames of reference, influenced search.

We considered two results from previous literature that were at odds with one another; haptic search efficiency was improved by either combining hands and redundancy or by dividing the hands with the shared division of labor to perform simultaneously. The question was simply, do the hands work more efficiently when together or when separated? Although the bar plot in Figure 3 initially suggested that search in a shared frame of reference was more efficient than in a single frame of reference, further statistical analysis revealed no significant difference between the two. The mean search times of one container when compared to two containers did not show any significant change in the efficiency of the search, which may indicate that the frames of reference utilized in this task simply have no effect on search times. The absence of such an effect suggests there may be additional nuances in how we direct our haptic attention which warrants further investigation. For example, separate hands may benefit from touching all the items quickly but comparison between them might be slower. Both hands working together might improve comparison, but the improvement might be offset by more slowly touching or competing actions between the hands within the search space.

Additionally, we tested whether the relative size between the target item and distractors predicted search times. We analyzed this by varying the volume of the target while systematically varying the dimensions that distinguished the target's uniqueness. This is best seen in Figure 4, where each target volume was tested against varying size distractors, and what made the target unique was either its length difference or its diameter difference. Search times showed a gradual decrease as the volume of the target increased; however, the dimension that distinguished the target was of significant importance to determining the time spent searching. An additive effect was observed between diameter and length searches, where the feature of length continuously resulted in longer search times when compared to diameter searches for the same target volume. This suggests that haptics is guided not just by the physical dimensions of the objects, but also by the feature in which those dimensions differed. The same volume-cylinder target was either more or less difficult depending on whether it differed from the distractor with respect to diameter or length.

LIMITATIONS & FUTURE DIRECTION

Although this study has provided valuable insights into the field of haptic search, it is important to acknowledge that there were several limitations. The study aimed to optimize ecological validity with the use of common materials, a naturalistic environment, and realistic search conditions. However, our experiment may not have fully captured and reflected the complexities of a real-world haptic search task and the items we often search for. In addition to that, the explored variables consisted of magnitude and frames of reference, which may exclude additional factors contributing to efficient searches, such as multi-sensory facilitation. Lastly, the population utilized for this study was solely composed of undergraduate students, limiting generalization to other ages and demographics.

Future research could delve into the positioning of the participant while searching. Positioning the search containers in non-standard positions regarding the body, such as a more leftward position or spreading the two container conditions further apart, should be pursued. This could provide more insight into how the body positioning and varying locations of search may influence the frame of reference and haptic efficiency.

CONCLUSION

By elucidating how different factors influence haptic attention and search, our findings contribute to the growing body of literature on haptic search and have implications for various fields, including prosthetics and human-computer interaction technologies. With further investigation into the dynamics of haptic attention and how frame of reference influences search, future research could advance our understanding of haptic perception and inform the development of these assistive technologies for individuals with sensory impairments. Given this, it is important to acknowledge that this field of research has received relatively little attention thus far, emphasizing the need for further investigation.

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Exploring the World by Touch: Guidance in Bimanual Haptic Search

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