Peri-Hand Space: A Helping Hand for Faster Object Recognition in Children

Nikola R. Klassen[1,2], Lindsay E. Bamford[1], & Jenni M. Karl[1]

[1]Department of Psychology, Thompson Rivers University, Kamloops BC, Canada

[2] Department of Psychology, Simon Fraser University, Burnaby BC, Canada

Author Note

Correspondence concerning this article should be address to:

Jenni M. Karl, Ph.D.

Department of Psychology

Thompson Rivers University

805 TRU Way

Kamloops BC, Canada, V2C 0C8

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Abstract

Visual processing is altered for stimuli located near the hands, in what is termed peri-hand space, but it is unclear whether peri-hand effects are stable across the lifespan. To investigate this, adults and 5- to 8-year-old children completed a naturalistic visual search task on a touchscreen monitor while wearing eye-tracking glasses. Upon recognizing a previously specified target image in a 12-image array, they released a pushbutton with their left index finger in order to reach out and touch the target. Participants completed the task twice, once with their right hand positioned on the monitor beside the visual array and once with their right hand positioned in their lap. Both children and adults were faster at recognizing the target when their right hand was near the array, but the magnitude of this peri-hand effect was greater in children than adults. The results are discussed in relation to the idea that object recognition may be facilitated within peri-hand space to a greater extent during childhood.

Keywords: Peri-Hand Space; Peri-Hand Effect; Near-Hand Effect; Dorsal Visual Stream; Development of Visual Perception; Visual Search; Eyetracking; Visual Object Recognition

Public Significance Statements:

- Altered visual processing near the hand was driven by faster target recognition after target fixation as opposed to faster visual search prior to target fixation.
- Both children and adults displayed faster target recognition for visual stimuli located near the hands.

- While adults were generally faster than children at recognizing a target image among an array of distractors, positioning the right hand near the visual array facilitated target recognition to a greater extent in children compared to adults

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Visual experience combines top-down and bottom-up processes such that prior knowledge, expectations, and motivations influence visual perception. One notable top-down influence on visual perception is the location of a visual stimulus relative to the body or a specific part of the body. For instance, the space surrounding the hand is referred to as peri-hand space and multiple aspects of visual processing appear to be altered when a stimulus is located within this space. Participants may spend more time looking at distractor stimuli near the hand, possibly because increased attentional resources are attributed to each distractor in order to ensure a more accurate search (Abrams et al., 2008; Thomas & Sunny, 2017). They may also recognize a stimulus near the hand more quickly, possibly due to faster visual processing of the stimulus once it has been fixated (Agauas et al., 2020; Bröhl et al., 2017; Thomas & Sunny, 2017). Similarly, they may display greater accuracy when identifying changes in a stimulus near the hand, possibly because of increased attention to, as well as working memory for, stimuli that are located near the hand (Tseng & Bridgeman, 2011). Thus, participants may complete a longer visual search when viewing stimuli within peri-hand space, but they may also recognize a target stimulus more quickly and accurately once they fixate on it due to heightened perceptual processing and working memory for the target.

One explanation for alterations in visual processing within peri-hand space is that they may result from the hand's ability to bias visual processing in favor of the rapid but low spatial resolution magnocellular visual pathway at the expense of the slower but high spatial resolution parvocellular visual pathway (Gozli et al., 2012). This in turn is thought to facilitate magnocellular dependent processes, including those that enable the rapid recognition of objects

(Chan et al., 2013; Kveraga et al., 2007) and the execution of visually-guided actions (for reviews see Brozzoli et al., 2014; Makin et al., 2007; Serino, 2019).

Object recognition is generally considered a perceptual function dependent on parvocellular input to the ventral visual stream. However, low spatial resolution information concerning the general size, shape, and luminance of a visual stimulus is thought to be rapidly transmitted to orbitofrontal cortex via subcortical magnocellular processes (Chaumon et al., 2014; Kveraga et al., 2007). This leads to the generation of crude predictions concerning the object's general identity that are then fed back to inferotemporal cortex in the ventral stream in order to constrain visual processing of more detailed high spatial frequency parvocellular inputs, thereby reducing computational demands and speeding object recognition (Bar et al., 2006; Kveraga et al., 2007; Peyrin et al., 2010). Thus, if objects located within peri-hand space are subject to a magnocellular processing bias they may be more readily recognized compared to objects located beyond peri-hand space, due to the activation of this rapid object recognition network (Chan et al., 2013).

The magnocellular pathway also provides prominent input to the dorsal stream of vision, which projects from occipital to motor cortex via the parietal lobe and helps to facilitate the production of visually-guided actions such as reaching, grasping, catching, and pointing (Goodale & Milner, 1992). The dorsal stream receives refined visual input from cortical areas V1, V2, and V3a, but also more crude visual inputs from a variety of subcortical areas, including the lateral geniculate nucleus, pulvinar, and superior colliculus (Mundinano et al., 2017, 2018; Maurer & Lewis, 2018; Warner et al., 2015). Both brain imaging and neuropsychological studies suggest that some peri-hand space effects may result from the rapid transmission of visual information to the dorsal stream via one or a combination of these subcortical pathways (Brown

& Goodale, 2008; Di Pellegrino & Frassinetti, 2000; Makin et al., 2012; Schendel & Robertson, 2004; Tamietto & Morrone, 2016). These rapid subcortical inputs to the dorsal stream may enable the initiation of a crude reaching movement towards a nearby object leading to the processing of visual, kinesthetic, proprioceptive, and motor signals by bimodal neurons in parietofrontal cortex, which then feedback to earlier cortical visual areas to refine the visual tuning of neurons in these areas to the physical contours of the object (Gallivan et al., 2019; Macaluso et al., 2000; Perry & Fallah, 2015; Perry et al., 2016, 2017), which in turn updates the dorsal stream to inform shaping and closure of the hand for grasping the object.

Given that the presence of the hand may bias visual processing toward magnocellular processes, and the role of the magnocellular pathway in object recognition and visually-guided actions, it seems plausible that the consistency and magnitude of peri-hand space effects may depend on the extent to which visual features of the object, as well as the configuration of the hand, afford action. Multiple studies report peri-hand space effects only if the hand near the stimulus maintains a configuration that facilitates an action such as grasping, including an open hand with the palm facing the object (Chan et al., 2013; Thomas, 2013), a power grasp (Agauas & Thomas, 2019; Thomas 2015, 2017), or a relaxed hand with the digits collected (Dosso & Kingstone, 2018). Images of objects that afford grasping (Chan et al., 2013) as well as those presented near the dominant hand of right-handers, that is, the hand most often used to perform skilled manual actions (Colman et al., 2017), can produce greater peri-hand space effects. Similarly, practicing skilled manipulatory movements with either the hand or a hand-held tool (Farnè et al., 2007) can enhance peri-hand space effects. Generating voluntary goal-directed actions even leads to the rapid remapping of peripersonal space by updating the relationship between visual and somatosensory stimuli in hand-centered coordinates according to the sensorimotor demands of the action (Brozzoli et al., 2009, 2010; Brown et al., 2008). Thus, the extent to which visual processing is altered within peri-hand space may depend on the extent to which features of the object and the hand are relevant for the production of visually-guided actions.

Thus far, peri-hand space effects have been studied primarily in adults. Yet, the neural substrates thought to enable peri-hand space effects are likely operational from early in development. Both the magnocellular and parvocellular pathways continue to undergo significant developmental change well into adulthood (Benedek et al., 2016), but both pathways appear to be functional at birth (Hammarrenger et al., 2003). In addition, subcortical inputs to the dorsal stream mature surprisingly early in primates and may even be the most prominent afferent input to the dorsal stream in young primates until they are overtaken by cortical afferents at later stages of development (Bourne & Rosa, 2006; Gordon & McCulloch, 1999; Maurer and Lewis, 2018; Mundinano et al., 2018; Tamietto & Morrone, 2016). Thus, children whose cortical afferents to the dorsal and ventral streams are not yet mature (Maurer & Lewis, 2018), might rely more heavily on subcortical afferents to support both rapid object recognition and the execution of visually-guided movements. If this were true, then it should be possible to detect peri-hand space effects in children. Furthermore, if placing a hand near a stimulus biases visual processing in favor of the subcortical magnocellular pathway, which is more prominent during early development (Maurer and Lewis, 2018), then it may even be expected that peri-hand space effects would be more pronounced in children compared to adults.

To test these hypotheses, adults and 5- to 8-year-old children wore a head-mounted eye-tracker and completed a naturalistic visual search task on a touchscreen monitor under two conditions; with their right hand positioned on the monitor beside the visual array (hand-close condition) and with their right hand resting in their lap (hand-far condition). The task required participants to find a previously presented target image within a 12-image array. The target and distractor images consisted of objects that were either graspable (ice cream cones, toys, wrenches, and cell phones) or ungraspable (horses, houses, boats, and people) and both the target and the distractors in the array were derived from the same category of objects. When the participant found the target in the array, they released a push button and reached out and touched the target image as quickly and accurately as possible with the left hand. Based on the research described above, we predicted that all participants would take longer to search through the visual array (Abrams et al., 2008; Thomas & Sunny, 2017), be more accurate at identifying the target object (Tseng & Bridgeman, 2011), and require less time to recognize the target after fixating on it (Bröhl et al., 2017; Thomas & Sunny, 2017) in the hand-close condition compared to the hand-far condition, particularly for graspable targets (Chan et al., 2013; Colman et al. 2017). We also predicted that these peri-hand space effects would be more pronounced in children compared to adults because subcortical visual inputs, including magnocellular inputs to the dorsal and ventral streams, may be more prominent in the developing brain (Bourne & Rosa, 2006; Tamietto and Morrone, 2016; Makin et al., 2012; Maurer & Lewis; 2018; Mundinano et al., 2018).

Methods & Materials

Participants

A power analysis was conducted in PANGEA software (https://jakewestfall.shinyapps.io/pangea/). Age (adult vs. child), Hand Position (close vs. far), and Target Graspability (graspable vs. ungraspable) were treated as fixed factors and Participant was included as a random factor nested under Age. The analysis revealed that a total sample size of *n* = 60 could be expected to detect significant medium-to-small effects (Cohen's *d* = 0.40) for the factors of Age (power = 0.751), Hand Position (power = 0.861), and Age x Hand Position (power = 0.861).

Adult participants were recruited from the psychology department at Thompson Rivers University (n = 36; males = 8, females = 28). The mean age of the adult participants was 21.4 years (SD = 5.8). Each was awarded 1% credit toward their psychology class for their participation. Five to eight-year-old children were recruited from the community through Facebook groups, posters, and word of mouth (n = 30; males =13, females = 17). The mean age of the child participants was 6.5 years (SD = 1.1). Each child participant was awarded a small prize and their parents were compensated with a $25 gift card to a children's clothing store.

All participants and/or their parents reported that they had normal or corrected-to-normal vison and did not have a sensory, motor, or neurological disorder. As past research has shown that peri-hand space effects in left-handers do not simply mirror peri-hand space effects in right-handers (Le Bigot et al., 2012), all participants were also self-reported to be right-handed. The Thompson Rivers University Human Ethics Research Committee approved all experimental procedures.

Apparatus and Stimuli

Visual stimuli were presented on a white square (1080 x 1080 pixels (p)) displayed at the center of a 24 inch E230t HP touchscreen monitor (total resolution 1920 x 1080 p) which was controlled by a standard keyboard and custom-made software programmed with Unity game engine and coded in Visual Studio using C# programming language. Stimuli consisted of black and white photographic images of graspable objects (ice cream cones, toys, wrenches, and cell phones) and ungraspable objects (horses, houses, boats, and people). Each image was centered in a transparent square measuring 150 x 150 p (2.6° x 2.6°). Upon pressing and holding the spacebar, a fixation cross appeared at the center of the white display square for 1000 ms. The fixation cross was then replaced by a single target image for 2000 ms. The target image was then replaced by a circular visual array consisting of 8 outer images located 17.6° from the center of the screen and 4 inner images located 8.0° from the center of the screen (Fig. 1). One of the outer images in the array was identical to the previously displayed target image while the remaining 11 images were distractor images derived from the same category of objects as the target image.

Design & Procedure

A mixed 2 x 2 x 2 experimental design was employed. Age (adult vs. child) served as an independent between-subjects variable while Hand Position (hand-close vs. hand-far) and Target Graspability (graspable vs. ungraspable) served as independent within-subjects variables. Dependent variables included Accuracy, Visual Search Time, and Target Fixation Duration.

Upon arriving at the lab, participants were fitted with a monocular, scene-based, head-mounted eyetracker designed to fit both child and adult participants (www.positivescience.com). The eyetracker consisted of two cameras, one that recorded the visual scene in front of the participant and one that recorded the relation between the corneal reflection and the pupil of the participant’s right eye. The eyetracking system was calibrated offline using the calibration software, Yarbus, affiliated with PositiveScience, and generated a rendered video illustrating the location and duration of participant fixations during the experiment at a sampling rate of 30 Hz.

Each participant sat facing the touchscreen monitor, the center of which was positioned in front of the participant’s nose approximately 40 cm from the participant’s eyes. The participant received verbal instructions on how to complete the visual search task and then completed a minimum of five training trials correctly before the experiment began in earnest. At the beginning of each trial, the participant pressed and held the spacebar on the keyboard with their left index finger. This initiated the appearance of a black fixation cross at the center of the screen for 1000 ms, followed by a single target image for 2000 ms, and then a circular array consisting of the target image and 11 distractor images from the same object category as the target image (Fig. 1). The participant was instructed to look for the target image in the array, and when they identified it, to release the space bar and reach out and touch it with their left index finger. Upon contacting the touchscreen monitor, the visual array disappeared, resulting in the completion of a single trial. When ready, the participant used their left index finger to depress the spacebar in order to initiate the next trial.

Participants completed two blocks of 40 trials in a counterbalanced fashion. They completed one block of trials with their right hand near the visual array (hand-close condition) and the other with their right hand resting in their lap (hand-far condition). In the hand-close condition, participants placed the lateral portion of their right hand on the deactivated right side of the touchscreen monitor so that their open and relaxed palm faced the visual array and their right elbow rested on a 2 inch paper pad on the table. The elevation of the paper pad was adjusted to the participant’s comfort by placing additional paper pads under the elbow as needed (Fig. 2). In the hand-far condition, participants placed their right hand in their lap. In a single block of 40 trials, each array was presented no more than five times, the target image was located at each of the 8 possible target locations within the array no more than four times, and each target image never appeared more than once. The order in which the target image and corresponding arrays were presented, the location of the target image within the array, and the image that served as the target within each array was randomized and counterbalanced across participants and trials.

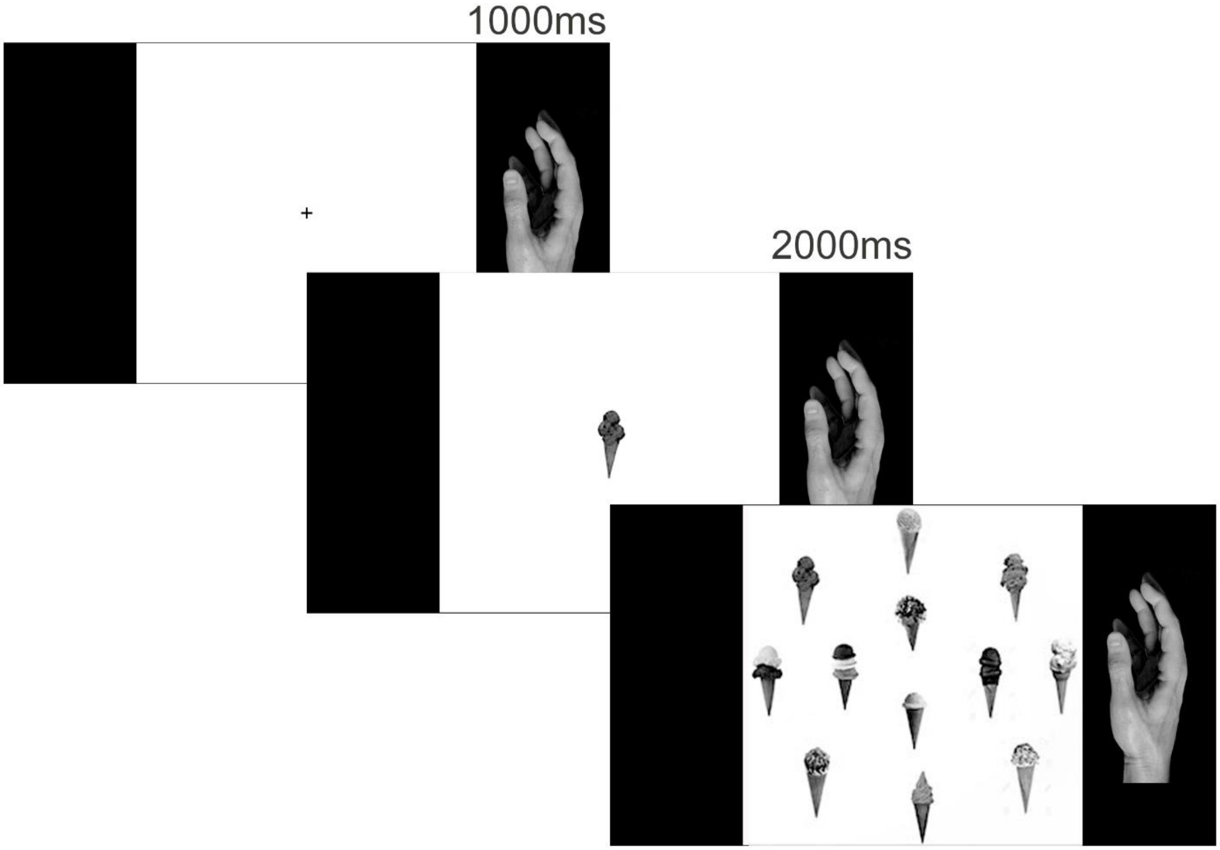

Figure 1. A depiction of the procedure used to display the visual stimuli. In the hand-close condition, participants placed the lateral portion of their right hand on the deactivated right side of the touchscreen monitor so that their open and relaxed palm faced the array. A fixation cross was presented at the center of the screen for 1000 ms, followed by a single image of the target object for 2000 ms, followed by a visual array consisting of the target object and 11 distractor objects from the same category as the target object, which remained on the screen until the participant touched the screen. In the hand-far condition, participants placed their right hand in their lap.

Data Analysis

Custom software recorded: 1) the time from when the visual search array appeared on the touchscreen monitor to when the participant released the spacebar with their left index finger; 2) the time from when the spacebar was released to when the participant’s left index finger touched the touchscreen; 3) whether the touch on the screen matched the target object’s location. The program polled when the spacebar had been released at a rate of 60 Hz.

Figure 2. A depiction of the experimental setup illustrating how participants placed the lateral portion of their right hand on the deactivated right side of the touchscreen monitor so that their open and relaxed palm faced the visual array in the hand-close condition.

Eyetracking data was collected from a head-mounted eyetracker because participants were required to reach out and touch the target on the touchscreen. Real interactions such as this can interfere with screen-based eyetrackers, because the arm and hand pass between the eyes and the eyetracker, which is generally mounted below the stimulus display, resulting in the loss of eyetracking data. Eyetracking videos were analyzed using manual frame-by-frame analysis in the software program Kinovea (Charmant, 2004) to determine the time of target fixation onset, which was defined as the first video frame during which the participant fixated within the 3.97 cm x 3.97 cm region of interest (ROI) centered on the target image and subsequently released the spacebar to reach out and touch the target image. Sometimes the first fixation landed on the border of the ROI and a judgement call was needed. Thus, eyetracking data from two adult and two child participants were analyzed by two trained experimenters (Hallgren, 2012). The inter-rater reliability for visual search times and target fixation durations (measures that are dependent on target fixation onset) were assessed using two-way, mixed, average-measures intraclass correlation co-efficients (ICC) with absolute agreeability. For Visual Search Time ICC = .998 and for Target Fixation Duration ICC = .915, indicating very high inter-rater reliability.

Three dependent measures were calculated for each trial. ***Accuracy*** was defined as the percentage of total trials on which the target object was correctly identified. ***Visual Search Time*** was defined as the total time from when the visual array appeared on the screen to when the participant first fixated on the target object within the array (target fixation onset). ***Target Fixation Duration*** was defined as the time from when the participant first fixated on the target in the array (target fixation onset) to when they released the spacebar in order to reach out and touch the target on the screen. Visual Search Time and Target Fixation Duration were only calculated for trials that the participant accurately identified the target object. Each dependent variable was transformed from raw scores into mean scores for each participant and analyzed using separate mixed analyses of variance (ANOVAs) in SPSS. The estimated marginal mean ± standard error are reported for all results.

Results

Separate mixed 2 x 2 x 2 ANOVAs were used to examine the effects of Age, Hand Position, and Target Graspability on three different dependent measures: Accuracy, Visual Search Time, and Target Fixation Duration. Data from six adult participants were excluded due to technology failures while data from seven child participants were excluded due to failure to follow instructions. Data from individual trials were excluded for any of the following reasons: (1) the participant did not select the correct target from the array (for measures of Visual Search Time and Target Fixation Duration only), (2) the participant accidentally released the spacebar prior to looking at the target image in the array, (3) the target was not visible in the eye-tracking video or the participant's visual fixations could not be observed, or (4) the participant did not look at the display during the trial. The mean, range, and total trials included in the final analysis are shown in Table 1.

	Trials Per Participant (Mean)				Trials Per Participant (Range)				Total Trials			
	Hand-Close		Hand-Far		Hand-Close		Hand-Far		Hand-Close		Hand-Far	
Age	G	UG	G	UG	G	UG	G	UG	G	UG	G	UG
Adults	16.7	16.1	16.7	16.7	10-20	9-20	11-20	10-20	501	484	501	500
Children	14.3	12.3	14.2	12.5	5-20	5-17	8-18	4-19	327	284	325	288

Accuracy

Accuracy refers to the percentage of total trials that the participant correctly identified the target. We predicted that both children and adults would be more accurate at identifying the target object in the hand-close compared to hand-far condition. All participants performed at greater than 50.00% accuracy with the exception of one child at 47.50% accuracy. The statistical analysis revealed a main effect of Age, F (1, 51) = 37.24, $p < 0.001$, Cohen's $d = 1.72$, and a main effect of Target Graspability, F (1, 51) = 27.76, $p < 0.001$, Cohen's $d = 1.49$ but no main effect of Hand Position, F (1, 51) = 0.30, $p = .58$ Cohen's $d = .16$, on Accuracy. Thus, regardless of hand position, adults (*94.29 ± 1.78%)* were more accurate than children (*77.83 ± 2.03%*) at identifying the target. There was no significant Age X Hand Position interaction, *F* (1,51) = 0.253, *p* = 0.62, Cohen's *d* = 0.14, but there was one significant interaction of Age x Target Graspability, *F* (1, 51) = 21.86, *p* < 0.001, Cohen's *d* = 1.32. Follow-up T-Tests revealed that, regardless of hand position, children were more accurate at identifying graspable (*82.72 ± 1.91%*) compared to ungraspable (*72.94 ± 2.39%*) targets, *t* (22) = 5.10, *p* < 0.001, Cohen's *d* = 1.62. In contrast, adults displayed no difference between graspable (*94.58 ± 1.68%*) and ungraspable (*94.00 ± 2.09%*) targets, *t* (29) = .65, *p* = .52, Cohen's *d* = 0.88, likely because of a ceiling effect in their performance (Fig. 3).

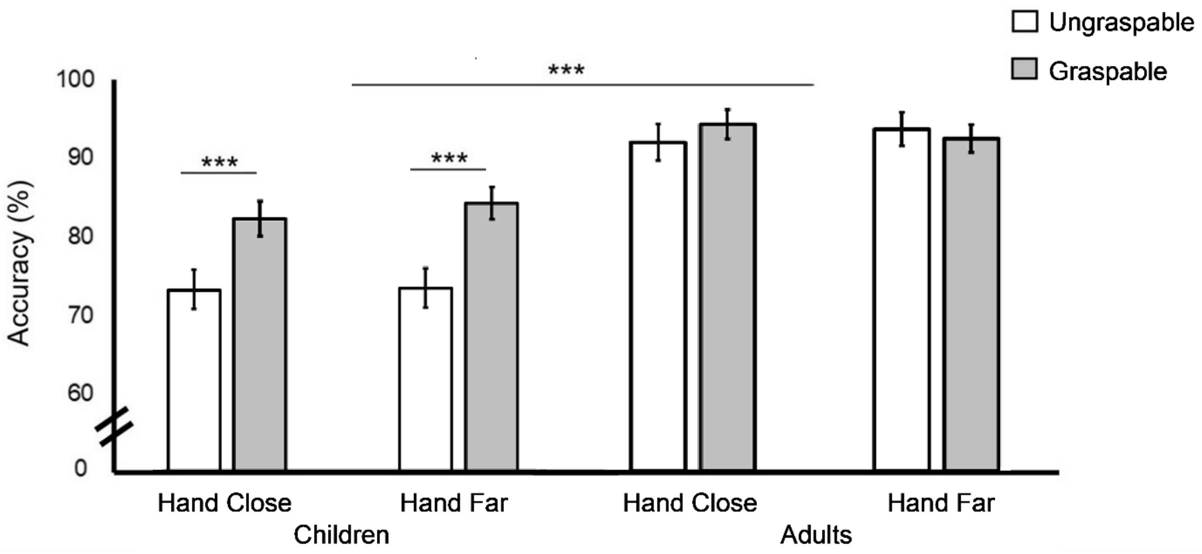

Figure 3. Accuracy of children (left) and adults (right) at identifying ungraspable (white) and graspable (grey) target objects in the hand-close and hand-far conditions. Note that Hand Position did not affect accuracy in either children or adults. Children were more accurate at identifying graspable compared to ungraspable targets whereas adults identified graspable and ungraspable targets with equal accuracy, likely due to a ceiling effect. * p < 0.5, ** p < 0.01, *** p < 0.001.

Visual Search Time

Visual Search Time is defined as the time from when the array appeared on the screen to when the participant first fixated on the target image (target fixation onset). We predicted that both children and adults would display longer Visual Search Times in the hand-close compared to hand-far condition. The statistical analysis revealed a main effect of Age, F (1, 51) = 88.92, $p < 0.001$, Cohen's $d = 2.66$ and a main effect of Target Graspability, F (1, 51) = 57.04, $p < 0.001$, Cohen's $d = 2.13$, but no main effect of Hand Position, F (1, 51) = 1.31, $p = 0.26$, Cohen's $d = 0.14$, on Visual Search Time. There were also no significant interactions. Thus, regardless of hand position, adults (*1265 ± 76ms*) displayed significantly shorter Visual Search Times than children (*2354 ± 87ms*) and both groups displayed shorter Visual Search Times when searching for graspable (*1582 ± 48ms*) compared to ungraspable (*2037 ± 78ms*) targets (Fig. 4).

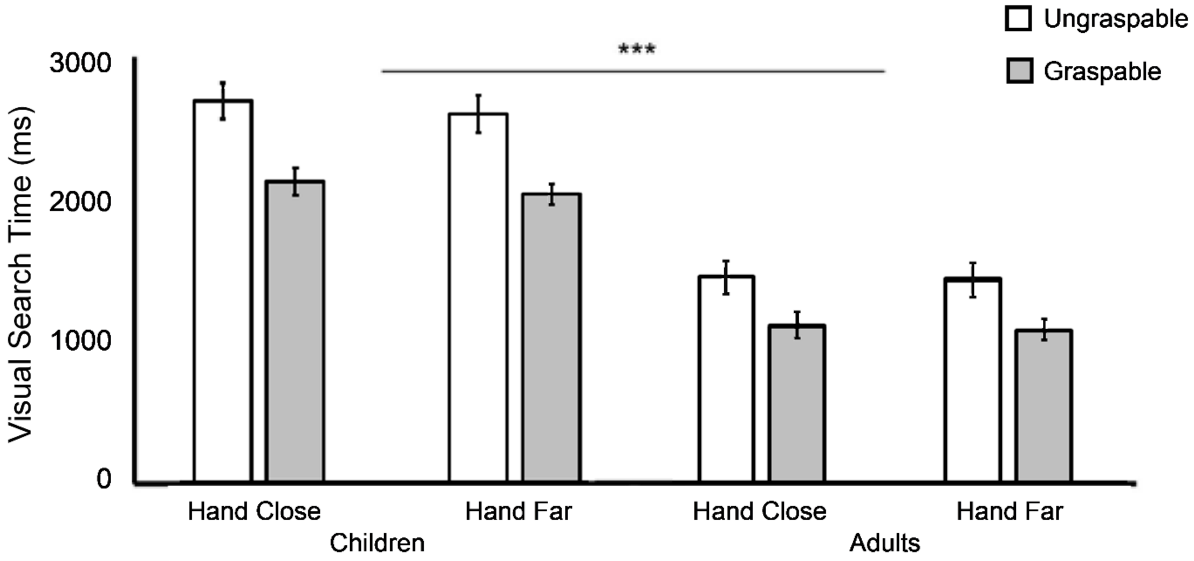

Figure 4. Visual Search Time of children (left) and adults (right) when searching for ungraspable (white) and graspable (grey) targets in the hand-close and hand-far conditions. Note that Hand Position had no effect on Visual Search Time in either adults or children. Children displayed

longer search times than adults, but both children and adults displayed shorter Visual Search Times for graspable compared to ungraspable targets. * p < 0.5, ** p < 0.01, *** p < 0.001.

Target Fixation Duration

Target Fixation Duration refers to the time from when the participant first fixated on the target image in the array (target fixation onset) to when they released the spacebar. This measure indicates how long it took participants to recognize that the image they were looking at was indeed the target and to decide to reach out and touch it. We predicted that both children and adults would display shorter Target Fixation Durations in the hand-close compared to hand-far condition. The statistical analysis revealed main effects of Age, F (1, 51) = 61.14, $p < 0.001$, Cohen's d = 2.21, Hand Position, F (1, 51) = 22.49, $p < 0.001$, Cohen's d = 1.34, and Target Graspability, F (1, 51) = 15.18, $p < 0.001$, Cohen's d = 1.10, on Target Fixation Duration (Fig. 4). Children displayed longer Target Fixation Durations (*775 ± 21ms*) than adults (*558 ± 18ms*), but both groups displayed shorter Target Fixation Durations in the hand-close (*641 ± 15ms*) compared to hand-far condition (*692 ± 15ms*) and for graspable (*646 ± 14ms*) compared to ungraspable (*687 ± 16ms*) targets.

There was also one significant interaction of Age x Hand Position, F (1, 51) = 8.27, p = 0.006 Cohen's d = 0.81, for Target Fixation Duration. Follow-up paired T-Tests revealed that both children, t (22) = 3.89, p = 0.001, Cohen's d = 0.92 and adults, t (29) = 2.10, p = 0.04, Cohen's d = 1.26, displayed shorter Target Fixation Durations in the hand-close compared to hand-far condition, but the moderating effect of hand position on Target Fixation Duration was greater in children compared to adults (Fig. 5). To further quantify this effect, we calculated the difference in Target Fixation Duration between the hand-far and hand-close conditions for each participant. A two-tailed t-test (equal variances not assumed) revealed a significant effect of Age on the magnitude of the peri-hand space effect, t (30.69) = 2.70, p = 0.010, Cohen's d = 0.81, where the magnitude of the peri-hand space effect on Target Fixation Duration was greater in children (*87 ± 22ms*) compared to adults (*21 ± 10 ms*).

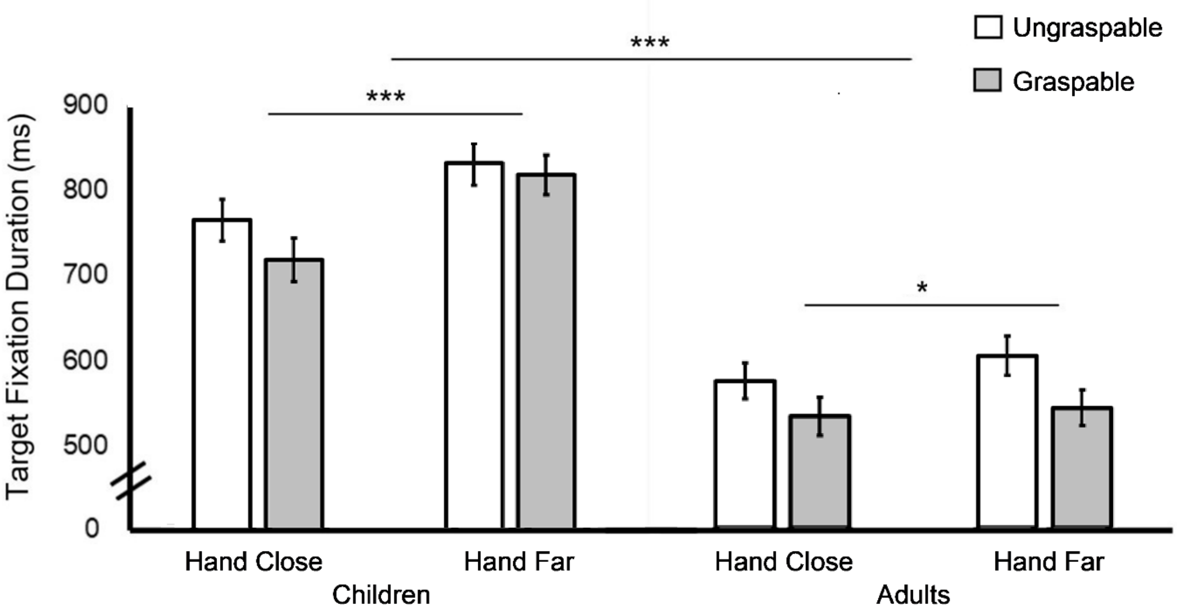

Figure 5. Target Fixation Duration of children (left) and adults (right) when identifying ungraspable (white) and graspable (grey) targets in both the hand-close and hand-far conditions. In comparison to adults, children fixated on the target for a longer duration before initiating a reach towards it. Still, both children and adults displayed shorter Target Fixation Durations in the hand-close condition compared to the hand-far condition, and the moderating effect of the nearby hand was significantly greater in children. * $p < 0.5$, ** $p < 0.01$, *** $p < 0.001$.

Additional Analyses

Perceived Difficulty of Graspable and Ungraspable Target Images

A subsequent analysis was conducted to determine whether the perceived difficulty of the graspable arrays differed from that of the ungraspable arrays. An online survey was administered using www.surveymonkey.com in which novel adult participants (n = 183) were required to find a target image within each of the 8 arrays and then subsequently rate the difficulty of each array on a 5-point scale from very easy (0) to very difficult (5). Ungraspable arrays received a mean score of 2.62 ± 0.06 while graspable arrays received a mean score of 2.38 ± 0.06. While this represents a minor difference with substantial overlap in participant responses for graspable and ungraspable objects, a paired samples t-test revealed that adult participants perceived the graspable arrays to be less difficult than the ungraspable arrays, t (182) = 4.37, $p < .001$, Cohen's d = 0.85.

Effect of Target Location on Target Fixation Duration and Visual Search Time

To determine whether Target Fixation Duration was shorter when the target was presented closer to the hand, we subsequently analyzed the effect of Target Location on Target Fixation Duration. The three target positions located on the right side of the visual array, closest to the hand, were grouped together and treated as the Target Close Location. The three target positions on the left side of the visual array, farthest from the hand, were grouped together and treated as the Target Far Location. The statistical analysis revealed a main effect of Target Location, F (1, 51) = 5.88, p = 0.019, Cohen's d = 0.13, such that Target Fixation Duration was shorter for the Target Close Location (*651 ± 14ms*) compared to the Target Far Location (*680 ± 17ms*). The main effect of age, F (1,51) = 56.70, $p < 0.001$, Cohen's d = 2.13, also remained intact such that children displayed longer target fixation durations (*775 ± 22ms*) than adults (*556 ± 19ms*). The interaction effect of Age x Hand Position, F (1,51) = 3.679, p = 0.061, Cohen's d =

0.542, was trending towards, but did not reach, statistical significance. There was no significant Hand Position x Target Location interaction, *F* (1, 51) = 3.149, *p* = 0.082, Cohen's *d* = 0.12, or Age x Hand Position x Target Location interaction, *F* (1, 51) = 0.08, *p* = .78 Cohen's *d* < 0.01. Follow-up paired samples t-tests revealed that the main effect of Target Location was driven largely by children *t* (22) = 3.080, *p* = 0.005, Cohen's *d* = 0.51, who displayed significantly shorter target fixation durations for targets located close (*705 ± 28ms*) as compared to far (*780 ± 32ms*) from the hand in the hand-close condition (Fig. 6). Adults also displayed shorter target fixation durations for targets located close (*531 ± 14ms*) as compared to far (*559 ± 20ms*) from the hand in the hand-close condition, (Fig. 6), but this did not reach statistical significance, *t*(30) = 1.855, *p* = 0.074, Cohen's *d* = 0.30.

A subsequent analysis was also conducted to determine whether Target Location also affected Visual Search Time. This analysis revealed no significant effect of Target Location *F* (1, 51) = 1.540, *p* = 0.220, Cohen's *d* = 0.35, on Visual Search Time. There were also no significant Hand Position x Target Location, *F* (1, 51) = 0.887, *p* = 0.351, Cohen's *d* = 0.27 or Age x Hand Position x Target Location, *F* (1, 51) = 2.333, *p* = .133 Cohen's *d* = 0.43 interactions.

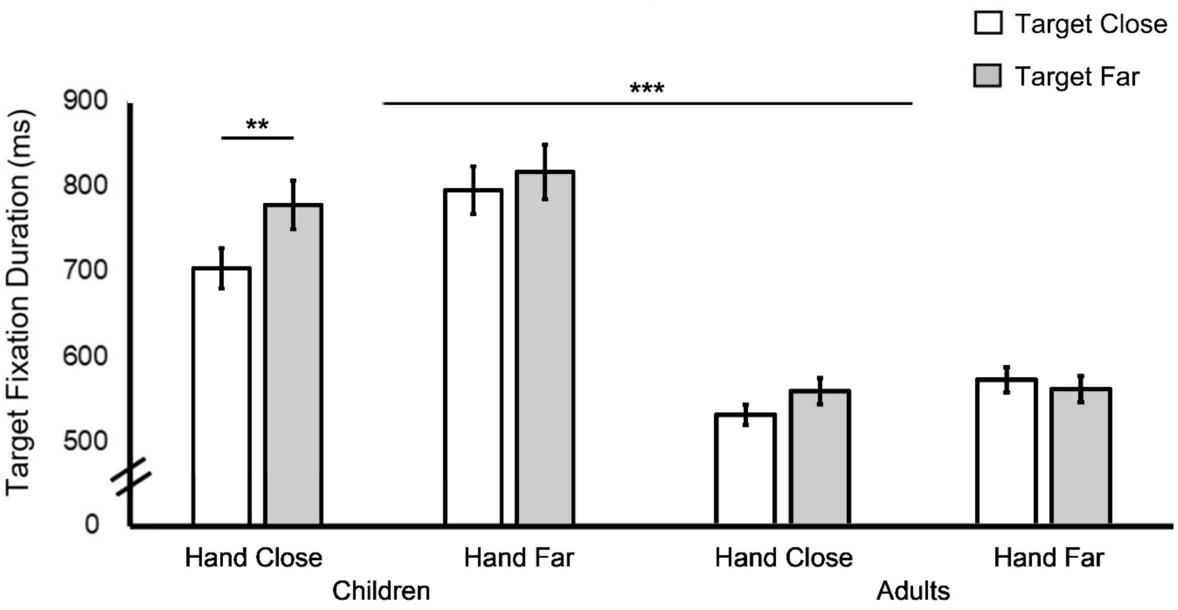

Figure 6. Target Fixation Duration of children (left) and adults (right) when the target image appeared on the right side of the visual array (Target Close condition, white) and on the left side of the visual array (Target Far condition, grey). In comparison to adults, children fixated on the target for a longer duration before initiating a reach towards it. Children displayed significantly shorter Target Fixation Durations when the target image appeared on the right side of the screen (Target Close condition) as compared to the left side of the screen (Target Far condition), but only when their right hand was positioned on the screen. * $p < 0.5$, ** $p < 0.01$, *** $p < 0.001$.

Discussion

Under certain conditions, positioning a hand near a stimulus may bias visual processing in favor of the subcortical magnocellular pathway (Chan et al., 2013; Gozli et al., 2012), which is thought to provide afferent input to both orbitofrontal cortex (Chaumon et al., 2014; Kveraga et al., 2007) and the dorsal visual stream (Brown & Goodale, 2008; Brown et al., 2009; Di Pellegrino & Frassinetti, 2000; Makin et al., 2007, 2012; Schendel & Robertson, 2004), in order to facilitate rapid object recognition (Kveraga et al., 2007) and the production of visually-guided actions (Brozzoli et al., 2014), respectively. In addition, subcortical visual pathways, including the magnocellular pathway, are functional from birth and provide relatively greater afferent input to cortical targets in the dorsal and ventral streams during development before receding in favor of cortical afferents at later ages (Maurer & Lewis, 2018; Gordon & McCulloch, 1999; Mundinano et al., 2017; Mundinano et al., 2018). Thus, it seems plausible that children would experience peri-hand effects, and that these effects might even be more pronounced in children compared to adults. Yet, to our knowledge, no previous studies have investigated whether visual processing is altered in peri-hand space in human children. Thus, we investigated peri-hand space effects on visual search accuracy, visual search time, and visual target recognition in children and adults as they completed a naturalistic visual search task. The results reveal that adults were generally faster than children at recognizing a naturalistic target among an array of distractors, but when they positioned their right hand near the visual array target recognition was facilitated to a greater extent in children compared to adults. These findings provide preliminary support for the idea that peri-hand space effects relating to visual object recognition are present, and may be more pronounced, during childhood.

The present study employed several innovative techniques to investigate peri-hand space effects in both children and adults. First, visual search tasks are commonly used to evaluate peri-hand space effects (Abrams et al., 2008; Davoli et al., 2017; Thomas & Sunny, 2017; Tseng & Bridgeman, 2011), but primarily measure accuracy and reaction time. By combining a visual search task with eye tracking we were able to deconstruct participant reaction times into two components, visual search time and target fixation duration. This allowed us to pinpoint which of these behaviors – target fixation duration – is more strongly influenced by the nearby presence of the right hand. Second, we used naturalistic stimuli that contained both high and low frequency spatial information and were highly recognizable to both children and adults as opposed to letters or geometric shapes. As a result, the task was operational for anyone over the age of 5 as evidenced by that fact that all but one child completed the task with greater than 50% accuracy. Third, because the production of goal-directed actions is known to rapidly re-map visual and tactile relationships centered on the hand (Brown et al., 2008, 2009; Brozzoli et al., 2009; 2010), and the posited function of peri-hand space is to facilitate goal-directed movements towards naturalistic objects (e.g., Brozzoli et al., 2014), we required participants to actually reach out and touch naturalistic photos of target images as opposed to press a button to indicate when they found a digitally manipulated photograph (Chan et al., 2013) or a geometric character/shape (Dosso & Kingstone, 2018; Thomas & Sunny, 2017). The combination of naturalistic stimuli and the requirement to perform a goal-directed action towards those stimuli likely served to increase both the power and ecological validity of our experimental task.

There were also some limitations that should be considered. First, peri-hand space effects are thought to be strongest when the palm (Brown et al., 2009) of the dominant hand is positioned near the target (Le Bigot et al., 2012). Thus, we asked participants to position their dominant right hand on the screen and to use their non-dominant left hand to reach out and touch the target. This, however, may have reduced the speed and precision of the participant's responses, as the non-dominant hand is generally less skilled (Bagesteiro & Sainburg, 2002; Elliott et al., 1994). Relatedly, if the function of peri-hand space is to facilitate goal-directed movements, then peri-hand space effects may be greatest when the hand near the stimulus is also used to reach out and act on the stimulus. As participants in the present study used the opposite left hand to reach out and identify the target, peri-hand space effects, particularly those sensitive to the action-related affordances of the stimuli, may have been reduced. Third, visual processing may be differentially altered depending on whether one or two hands are positioned near the stimulus. For example, Bush & Vecera (2014) found that when two hands framed a visual display, participants' attention was distributed more evenly across the display and temporal discrimination within that space was improved, which they posit was due to biasing of visual processing towards the magnocellular pathway. Perhaps if we had asked participants to position both hands on the screen peri-hand space effects would have been enhanced for targets presented on both the right and left sides of the display. Nonetheless, all of these experimental manipulations affected all participants equally and did not bias the results in any consistent fashion. Still, future research could address these issues by asking participants to complete the task with the dominant hand, non-dominant hand, and both hands near the display while also using a hand positioned near the display to reach out and identify the target in the array.

Somewhat surprisingly, we found that positioning the right hand near the visual array did not influence the accuracy or speed of visual search in either children or adults. These results conflict with previous findings (Abrams et al., 2008; Thomas & Sunny, 2017; Tseng & Bridgeman, 2011), which suggest that participants may display greater accuracy at detecting a change in visual stimuli, as well as a prolonged visual search due to slower disengagement of distractor images, when a hand is positioned near the stimulus display. Rather, our results align more closely with Andringa et al. (2018), who found that when adults positioned their hands on a screen while completing a visual search task with more naturalistic visual scenes, it had no effect on their ability to accurately identify a target image within the scene. These discrepancies may be due to several factors. First, the studies that did find peri-hand space effects on accuracy and visual search time did not use eyetracking, but instead calculated visual search time based on the number of distractor images in the array and the size of the screen. Thus, our measure of visual search time may be considered more direct but would likely have generated substantially different results from these earlier studies. Second, in the studies that found a peri-hand space effect, both the target and distractor images appeared at unpredictable locations on the screen during the visual search task. The images in our experiment appeared at consistent locations (the 8 outer locations in the circular array). As such, our participants were likely better able to predict where they should direct their visual attention while searching through the array, which could have optimized visual search time prior to fixating on the target regardless of the position of the right hand. Third, both the study by Andringa et al. (2018) and the present study used more complex and naturalistic visual stimuli that may have placed greater demands on visual processing in order to find and identify the target compared to studies that used only one or a small number of less detailed images or simple geometric shapes. This could have disproportionately affected both working memory for the target (and thus visual search accuracy), as well as the amount of time required to search through the array of distractors, compared to other measures of visual processing in peri-hand space.

We consistently found that visual search accuracy, visual search time, and target recognition were enhanced when participants searched for graspable targets compared to ungraspable targets, regardless of hand position. Specifically, all participants tended to display shorter visual search times and target fixation durations when searching for graspable targets. In addition, children, but not adults, were more accurate at identifying targets that were graspable. However, subsequent analyses revealed that our ability to interpret these results is limited because the graspability manipulation used in the present study may have been confounded. A separate sample of adult participants reported that they perceived the graspable targets to be slightly less difficult to find than the ungraspable targets. There are two ways to interpret this. First, it may be that the graspable targets biased visual processing towards the magnocellular pathway, priming action-relevant object representations in both the ventral (Chan et al., 2013; Kveraga et al., 2007) and dorsal streams (Almeida et al., 2010; Freud et al., 2020; Kourtis et al., 2018; Macdonald & Culham, 2015), thereby improving the accuracy, visual search time, and speed of object recognition for graspable targets, which could have in turn lowered the perceived difficulty of finding graspable targets. In this case, no confound would be present. Alternatively, it may be that the graspable stimuli really were slightly easier to identify, resulting in greater accuracy, shorter visual search times, and shorter target fixation durations for graspable targets, in which case a confound would be present.

We did not specifically ask participants why they might have perceived the graspable targets to be less difficult to find, but we can speculate that there might be at least two possible contributing factors. First, low-level visual features such as image luminance, contrast, and texture can influence visual attention when recognizing and categorizing visual stimuli (e.g., Kollmorgen et al., 2010). Because we chose to use photographs of naturalistic stimuli, it was not possible to completely control the low-level visual features of the stimuli. Thus, we cannot exclude the possibility that differences in perceived difficulty could be related to slight differences in the complexity of low-level visual features of the graspable vs. ungraspable targets used in the present study. Second, behavioural and neuroimaging work by Konkle and colleagues (Konkle & Caramazza, 2013; Konkle & Oliva, 2011, 2012a,b; Long et al., 2019) has revealed that both adults and children are faster to recognize inanimate objects if their visual size (as presented on a screen) is congruent with their real-world size. In the present study, the visual size of graspable objects (ice cream cones, toys, wrenches, and cell phones) was more congruent with their relatively small real-world size. In contrast, the visual size of the ungraspable objects (horses, houses, boats, and people) was incongruent with their much larger real-world size. Konkle and colleagues propose that this normative size congruency effect may also be due to top-down influences on visual processes involved in object recognition. Thus, it is possible that the lower perceived difficulty, increased accuracy, faster visual search time, and shorter target fixation durations observed for graspable targets might be due to the fact that the graspable objects were more congruent with their normative size than the ungraspable objects in the present study.

Despite potential confounds between the graspability, low-level visual features, and normative size of the target images, the fact that we did not find any significant hand position by graspability interaction effects suggests that positioning the right hand near the visual array did not bias visual processing in favor of the graspable targets, at least under the conditions of the present study. Nonetheless, future research should address these issue by controlling for low-level visual features and normative size congruency across both graspable and ungraspable stimuli. The approach of Macdonald and Culham (2015), who used graspable objects (e.g., hammers) and manipulated versions of those same objects (e.g., “schmammers”) in order to manipulate the graspability of visual stimuli without introducing confounds related to normative image size and/or low-level visual complexity, may be particularly useful.

Despite the aforementioned limitations, the most notable finding from the present study was that both adults and children recognized the target object more quickly after fixating on it in when their right hand was positioned on the right side of the visual array. Subsequent analyses revealed that this effect was strongest in child participants when the target appeared on the right side of the screen, closer to the right hand. Meanwhile, visual search times were unaffected by either hand position or target location. Together, these results are in agreement with numerous previous reports that adults are faster at identifying targets located in peri-hand space (Bröhl et al., 2017; Chan et al., 2013; Reed et al., 2006, 2010; Thomas & Sunny, 2017). They also extend these previous findings by revealing that a similar effect also occurs in school-aged children.

These results align well with the attentional prioritization theory of peri-hand space (Reed et al., 2006), which posits that attentional monitoring does not simply shift to regions of space near the hand, but rather, that the salience of stimuli in peri-hand space is enhanced (receives attentional prioritization) due to the ability of such stimuli to activate bimodal, in addition to unimodal, neurons in dorsal stream networks, which may lead to stronger activation of stimulus representations for, and thus faster recognition of, stimuli located near the hand. If the presence of the hand were to simply shift attentional monitoring towards the hand, then we would expect that participants would display shorter visual search times, but not target fixation durations, when targets appeared near the hand. That we found the exact opposite lends support to the idea that attentional prioritization, but not general attentional monitoring, is enhanced in the space near the hand.

Our findings also align with the magnocellular processing theory of peri-hand space (Chan et al., 2013; Gozli et al., 2012), which argues that positioning the hand near a stimulus causes top-down biasing of visual processing in favor of the magnocellular visual pathway. Because magnocellular neurons possess large axons and large receptive fields (Maunsell et al., 1990) they are able to rapidly transmit low spatial frequency information to overlying cortical targets. One of which is thought to be the orbitofrontal cortex, which may serve to facilitate the rapid recognition of visual objects (Chaumon et al., 2013; Kvergara et al., 2007). Another is the dorsal visual stream (Maunsell et al., 1990), which may help to facilitate the rapid execution of visually-guided actions towards objects near the hands (Brozzoli et al., 2014). Previous research has demonstrated that adults more rapidly recognize artificial visual stimuli containing only low spatial frequency information (stimuli biased towards the magnocellular pathway) when located near the hands (Chan et al., 2013), but our results are the first to demonstrate this effect in both adults and 5- to 8-year-old children using more naturalistic stimuli that contain a combination of both low (magnocellular biased) and high (parvocellular biased) spatial frequency information.

Finally, the most novel finding from the present study is that positioning the right hand near the stimulus facilitated target recognition to a greater extent in 5- to 8-year-old children than it did in adults. The moderating effect of age on this peri-hand space effect could be explained by incorporating a developmental perspective into both the attentional prioritization and magnocellular theories of peri-hand space. For instance, subcortical magnocellular afferents to overlying cortical targets are relatively more prominent during development compared to in adulthood (Born & Bradley, 2005; Maurer & Lewis, 2018; Mundinano et al., 2017). Thus, if positioning the hand near a visual stimulus does bias visual processing towards subcortical visual pathways (Brown et al., 2008; Makin et al., 2012; Perry & Fallah, 2017), specifically the magnocellular pathway (Chan et al., 2013; Gozli et al., 2012), this would produce more pronounced peri-hand space effects in children compared to adults. Similarly, as we age subcortical visual projections typically recede in favor of more refined visual projections from the occipital lobes (Born & Bradley, 2005; Maurer & Lewis, 2018), which could lead to a reduction in the relative magnitude of peri-hand space effects in neurotypical adults.

Conclusion

In conclusion, the results of the present study are in agreement with previous findings that peri-hand space effects are strongly influenced by numerous contextual factors as well as the methods used to quantify them (e.g., Andringa et al., 2018; Chan et al., 2013; Dosso & Kingstone, 2019; Perry et al., 2015; Thomas & Sunny 2019). The present findings extend previous research by revealing that the age of the participant may also contribute to the magnitude of peri-hand space effects, which may be more prominent in childhood. As this is the first study, to our knowledge, to investigate peri-hand space effects in children, future research should aim to replicate the present results in more children, across a larger age range, with a greater variety of visual tasks; correlate changes in visual processing in peri-hand space with changes in the organization of peri-hand space networks in the dorsal and ventral streams throughout development, and; resolve whether or not altered visual processing in peri-hand space might serve to facilitate the development of goal-directed movements in typically developing children.

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