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Comparing attention and eye movements towards real objects versus image displays

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by

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Abstract

Images of objects are commonly used as proxies of real objects in studies testing attention and eye movements. However, a lot of modern research discovered neural and behavioral differences in perception of real objects and their pictorial representations. The goal of the current investigation is to verify if covert attentional orienting and patterns eye movements are influenced by proprieties of real objects such as stereoscopic cues and tangibility. In the first experiment a modified version of the Posner cueing task was used to verify differences in spatial orienting between real tools and fruits and vegetables and their pictorial representations. The result showed that participants were faster to detect a target on the left side of real objects rather than when displayed as images, however, only if real objects were presented in a reachable distance. Therefore, the first study showed that the graspability of stimulus magnifies the leftward bias of visuospatial attention also known as 'pseudoneglect'. The second study compared patterns of eye movements in categorization and grasping task of real familiar tools and their images and stereoscopic displays. The results showed that if participants were asked to categorize objects then the display format of those items did not affect patterns of eye movements. However, when the participants were asked to grasp the objects then their eye movements were more focused on the handles of real objects rather than any other display format. Therefore, the both experiments showed the importance of tangibility of stimuli on perception. Moreover, the two studies used novel stimuli presentation systems that can be used in the future research studies testing other aspects of perception of real objects and their pictorial representations.

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General Introduction

Attention

We live in a cluttered world and limits in processing capacity lead to the need to select only the most relevant objects or locations for further processing. Attention serves both to enhance the processing of relevant information, and to filter our other information that is irrelevant or distracting (James, 1890). Furthermore, James (1890) pointed out that we pay attention either voluntary or our attention may be attracted by some external events not under our control. Nowadays, we called the former endogenous and the latter exogenous attention (Carrasco, 2011). Moreover, attention can be directed towards stimuli (or locations) in a ‘bottom-up’ manner based on the physical salience of the object with respect to the background (i.e., bottom-up control of attention), or in a ‘top-down’ manner, based on the relevance of the object for our current goals and intentions (i.e., top-down control) (Carrasco, 2011; Q. Chen, Weidner, Vossel, Weiss, & Fink, 2012; Petersen & Posner, 2012; Posner & Petersen, 1990). Moreover, attention can be allocated ‘overtly’ where it is accompanied by eye movements, or ‘covertly’ while fixating at a certain location in the visual field (Carrasco, 2011).

The advances in experimental psychology and neuroimaging in the last three decades allowed researchers to expand our understanding of attention as a conscious system of processing information and they highlighted three components of attention: alerting, executive control and orienting (Petersen & Posner, 2012; Posner & Petersen, 1990). In our everyday life we need to maintain a vigilant or alert state in order to be ready to process high priority signals from our environment. As shown in many studies using cues or warning signals, before the target appears, attention is executed faster as measured by response time which also can cause a higher error rate (Posner & Petersen, 1990). Alertness cannot only be caused by cues but also carcadian rhythms and overall well-being of an observer. Another function of attention is our ability to maintain focus on a particular stimulus or information and do not get distracted by other factors, in other words, attention operates as an executive control mechanism (Petersen & Posner, 2012). This process can include target detection, resolution of conflict, self-regulation and any other top-down control function. Finally, the main goal of the orienting system is biasing attention to a particular modality or spatial location (visual spatial attention) without any change in eye or head position.

There is a large group of research devoted to study attention allocated to features such as contrast (Carrasco, Penpeci-Talgar, & Eckstein, 2000), depth (Kawabata, 1986; Viswanathan & Mingolla, 2002), and motion (Cavanagh, 1992) (for a comprehensive review of feature based attention see also, Carrasco, 2011). Other studies are interested in attention concentrated on objects and within objects' boundaries (Z. Chen, 2012; Scholl, 2001; Weger, Abrams, Law, & Pratt, 2008). Finally, many studies investigate how attention is distributed in space through overt and covert orienting (Q. Chen et al., 2012; Kowler, Anderson, Dosher, & Blaser, 1995; Posner & Petersen, 1990; Posner, Snyder, & Davidson, 1980). Importantly, those research of different aspects of visual attention show that we have selective mechanisms to code for features, objects in the visual space and spatial locations.

Measuring eye movements

Eye movements are required to direct regions of the external environment that are relevant for further processing into the fovea (Deubel & Schneider, 1996; Orquin & Mueller Loose, 2013). Eye movements are generated via six muscles, each of which are attached at different positions on an eyeball (Duchowski, 2007). The neural signal to move the eyes is initiated in the medulla and supported by cerebellum and then the final command to move an eye is decided by neurons of Frontal Eye Fields (Duchowski, 2007). Importantly, eye movements are tied closely to attention (Deubel & Schneider, 1996; Kowler, 2011; Orquin & Mueller Loose, 2013). Eye moments may be guided by both items or locations that are physically salient (Itti & Koch, 2000) as well as those that are relevant to the goals and intentions of the perceiver (Henderson, Williams, Castelhano, & Falk, 2003; Kowler, 2011; Land, 2006; Orquin & Mueller Loose, 2013).

Recent advances in eye tracking technology and methodology have made it possible to study a variety of behaviors performed by the human oculomotor system during different types of tasks including object scanning (Underwood, Chapman, Bowden, & Crundall, 2002; Yarbus, 1967), reading (Heller & Radach, 1999; O'Regan, 1989; Rayner, 1978, 2009), driving (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), playing sports (Mann, Williams, Ward, & Janelle, 2007) and performing daily activities (Land, 2006; Land & Hayhoe, 2001). Eye movements are typically analyzed in three sub-categories: fixations, saccades and smooth pursuits (Kowler, 2011). Fixations are typically defined as eye movements over a particular region of interest through certain amount of time (Pritchard, Heron, & Hebb, 1960; Salvucci & Goldberg, 2000).

Saccades are rapid eye movements between fixation, and their amplitude and velocity can be influenced by attention or learning (for review see, Kowler, 2011). Finally, smooth pursuits represent patterns of eye movements during tracking a moving target eye movements (Kowler, 2011). During fixations we can also observe small, rapid eye movements, which include tremors, drifts, and microsaccades (for review see, Rucci & Poletti, 2015), however, these movements are so rapid that it is difficult to link them to high-order cognitive functions (Rucci & Poletti, 2015; Salvucci & Goldberg, 2000). Therefore, analyzing fixations over a longer period of time, for example 80 ms can simplify complexity of oculomotor behaviors and allow for the understating of cognitive processes governing these visual functions (Salvucci & Goldberg, 2000).

Perception and action

In late 19th and at the beginning of 20th century American philosophers started questioning the idea that what we experience and understand is merely what we see (Fisch, 1996). William James was one of the first thinkers who rejected the idea that the human mind is a mind of a spectator. James postulated that cognitive undersetting of the world involves not only visual perception but also its interplay with emotions, volition and action (James, 1890).

In the realm of cognitive psychology the importance of action in perception started from works of James J. Gibson (1979) and his student Donald Norman (2002). James Gibson proposed the ecological approach to visual perception (1979). Accordingly, any living thing in an environment, including humans, see features and objects in order to act upon them because only through such interaction can achieve their goals or accomplish their daily tasks. The approach was based on the idea of affordance. Gibson coined the term ‘action affordance’: any animal in any given environment is an agent ready for a possible interaction and moreover that agent may or may not be aware of the fact that features in the environment offer affordance, i.e. possibility for interaction. Gibson pointed out that affordance is an objective feature of an object directly perceived as such by any agent (for example, a hammer will be grasped in the same way by anyone). Norman (2002) constrained that term and called it perceived affordance. Norman pointed out that an agent must be aware of object that offer affordance in the environment. Therefore, affordance refers to the relationship between agent’s cognition and potentially action related features in their environment (Norman, 2002).

The idea of affordance and perceived affordance has been both criticized and appreciated by many modern researchers (Creem-Regehr & Kunz, 2010). Importantly, the impact of those theories has not only been presented in designing questions in cognitive neuroscience and psychology but also in creating user friendly (having affordance) human computer interfaces or teaching robots to properly interact with objects in an environment by looking for features that promote affordance in objects (Nye & Silverman, 2012).

In the modern philosophical discussion about the interaction between visual perception and motor control of actions Alva Noë (2006) proposed enactive approach to perception. In this approach seeing is an active process and requires not only physical activity but more importantly our activity in thinking about what we are perceiving. Similarly to Gibson and Norman, Noë (2006) argues that our existence in any given environment depends on our ability to interact with its features. However, contrary to Gibson he argues that we do not directly perceive features of objects that offer affordance but rather we use or understanding of our sensorimotor skills and our knowledge and experience in planning and executing our action. The enactive approach to perception fits well with another modern approach, that is, the embodied view on cognition (Barsalou, 2010; Proffitt, 2006, 2013). Accordingly when planning any action in our environment we take into consideration all factors related to features of an object that imply affordance, and also our capabilities of our body (e.g., a reach of our arms, power of our grip) and even emotional state (Proffitt, 2013; Stefanucci & Proffitt, 2009). The embodied view states that any action that we observe or want to perform is first represented in the brain and the same neural networks that govern action execution are involved in action representation.

Empirically the importance of action in visual perception has been verified by the two visual streams hypothesis (Mishkin, Ungerleider, & Macko, 1983) and its modifications (Goodale & Milner, 1992; Whitwell, Milner, & Goodale, 2014). The original theory states that we recognize objects that enter our retina in neurologically defined ventral stream that starts in the area V1 of visual cortex and projects to inferior temporal cortex. The information where an object is located in a visual field is carried by the dorsal stream beginning in V1 through middle temporal cortex, and middle superior temporal cortex to posterior parietal cortex. Goodale and Milner (1992) revised the original theory and pointed out that the dorsal pathway is not only responsible for locating objects but also for developing and administrating sensimotor plans how to use it. Importantly, the theory was based on the behavioral performance of neurological participants. The existence of the dorsal function stream was documented by the work with a patient DF who had lesions of temporo-ocipotal lobe in both hemispheres (Whitwell et al., 2014). The patient could not recognize objects presented in front of her but she could recognize them during grasping. The proof for the functional ventral stream comes from optic ataxia patients with damage to superior parietal cortex who could recognize and named objects but they had difficulties manually interacting with them in particular they could not grasp objects properly for the action they were asked to perform with them (Creem-Regehr & Kunz, 2010).

Real objects and their images

In early development we are first exposed to real objects in our surroundings. We learn how to interact with the world by interacting with real objects. Later on we learn that images are also objects that can represent other objects. This become evident in the study conducted by DeLoache, Pierroutsakos, Uttal, Rosengren, and Gottlieb (1998) who in series of experiments showed that infants when presented with images of real world objects explored them as they were tangible. Only later around 19 months of life they began to understand the nature of a photograph and start pointing to objects presented in the image. These developmental studies show that one of the most important differences between the two classes of objects is affordance.

A majority of previous research have been studied the influence of affordance on perception using images of manipulable objects such as tools (Lewis, 2006). It has been established that they automatically recruit specific visuo-motor areas in the brain (Gallivan, McLean, Valyear, & Culham, 2013; Lewis, 2006). It has been also discovered that they bias attention on both neural (Handy, Grafton, Shroff, Ketay, & Gazzaniga, 2003) and behavioral levels (Garrido-Vasquez & Schubo, 2014). However, images of objects can only represent semantic meaning of an object and few other features such as 2D size and closely match color. It still very interesting that, by using images of objects, many researchers could detect activity of motor regions of the brain even when images of objects are merely proxies of real objects.

Real objects offer an observer physical affordance that can not be included in pictorial displays. Further, unlike two-dimensional (2D) images, real objects, possess additional three-dimensional (3D) shape cues (Chainay & Humphreys, 2001), they vary in their surface texture and compliance (Cant & Goodale, 2011), and they have a definite size, weight, distance and location relative to the observer (Konkle & Oliva, 2011) – factors that are critical in planning appropriate grasp actions.

Recent studies have shown both perceptual differences between real objects and their images in human observers (Bushong, King, Camerer, & Rangel, 2010; Snow, Skiba, Coleman, & Berryhill, 2014) and primates (Mustafar, De Luna, & Rainer, 2015). Moreover, other studies found differences in patterns of neural activity measured by fMRI in human (Snow et al., 2011) and using single cell recording technique in rodents (Aghajan et al., 2015). As Snow et al. (2014) investigated real objects are recalled and recognized better than both image displays and line drawings of those items. Bushong et al. (2010) found that real snack foods are valued more than pictures of the same items in a bidding task. Mustafar et al. (2015) showed that real object receive longer initial fixations in comparison to their computerized images in a free viewing task conducted on primates. Snow et al. (2011) discovered that real objects are not a subject to the repetition suppression effect, that is, a decrement in Blood Oxygenated Level Response after many repetitions of the same stimuli. Finally, Aghajan et al. (2015) observed more robust hippocampal activity in rodents when exploring real world maze vs. maze presented in virtual reality. The discussed research studies provide enough evidence that images are not perfect proxies of real object, however, more research are needed to verify those differences in other aspects of cognition and behavior.

Current investigation

This thesis presents two research projects that address two critical questions of whether, and how, attention and eye movements are drawn to real, familiar, graspable and manipulable objects (i.e., a real hammer that could be grasped and wielded) versus matched image displays. In particular, stereo displays can appear very similar to real objects in terms of their visual inputs, but do not afford genuine action. A number of recent research studies that have contrasted directly responses to images versus real objects, suggests that images may not be appropriate proxies for their real-world object counterparts (Aghajan et al., 2015; Bushong et al., 2010; Mustafar et al., 2015; Snow et al., 2011; Snow et al., 2014). Images are merely representations of tangible real-world exemplars and they cannot be acted upon.

The studies presented in the section above illustrated that real object differ from 2D images in variety of aspects and have different influence on perception, memory, decision-making, and neural representation. Therefore, relying on images may limit our understanding of mechanisms of attention, and eye movement patterns, as they operate in naturalistic contexts. The results of the presented studies will serve as a platform for developing, and possibly updating, current theories of attention, to take into account potential modulatory effects of the motor system, rather than relying on images, which stimulate the visual system in relative isolation. This contribution is important because only by using realistic stimuli can we start to reveal the integrated workings of the perceptuo-motor system.

This thesis consists of two research studies:

Experiment 1: **Comparing spatial attention towards real objects versus images**

Experiment 2: **Differences in fixations during grasping and categorization tasks with real object, 2D and 3D.**

Experiment 1: Comparing spatial attention towards real objects versus images

Introduction

Object affordances bias attention

Many objects in our everyday life offer features that support physical interaction. The characteristics of an object that support action have been referred to ‘action affordances’ (Gibson, 1979). Manipulable objects such as tools are special because they have specific function and motor action routine that is closely tied to the identity of the object (Creem & Proffitt, 2001; Guillery, Mouraux, & Thonnard, 2013; Tucker & Ellis, 1998). For example, for an agent in the real environment, a nearby saw affords sawing and it is wielded with a characteristic left-right arm motion. Therefore, tools have strong functional specificity in contrary to other familiar and graspable types of objects. For example, although a cucumber could be grasped and used, natural objects like vegetables do not have a specific function and are not associated with a typical motor routine (Skiba & Snow, 2016).

A number of studies also showed that viewing a tool automatically facilitates motor responses. For example, human observers are faster in a motor task when presented with a tool that handle is directed towards their performing hand, even when the shape of the object is irrelevant to the observer’s task (Tucker & Ellis, 1998, 2001). These effects are related to object affordance and are thought to arise due to the automatic activation of visuo-motor neural network predominately located in the dorsal visual stream responsible for object manipulation (Gallivan, McLean, & Culham, 2011; Handy, Grafton, Shroff, Ketay, & Gazzaniga, 2003). The dorsal visual stream in known not only for accommodating neural processes involved in planning and executing action but also for controlling visuospatial attention (Posner 2012, Craighero, Fadiga, Rizzolatti, & Umilta, 1999; Rizzolatti, Riggio, Dascola, & Umilta, 1987). Therefore, it is possible that viewing manipulable objects may bias visuospatial attention and such observation have been reported in imaging studies (Handy et al., 2003) and behavioral experiments (Garrido-Vasquez & Schubo, 2014). According to a classic object competition model (Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997) features of objects compete for neural processing within visual and motor systems that represent the most prominent characteristic objects that receive most neural representation and are selected for further processing. Therefore, proprieties of object that imply interaction may attract more neural processing across the visual and motor parts of the brain and visuospatial attention is oriented towards those futures of objects that imply action affordance (Adamo & Ferber, 2009; Handy et al., 2003).

Surprisingly, however, ‘object affordances’, and their influence on attention, have been mostly studied using computerized images or line drawings of manipulabe objects, rather than tangible real-world exemplars (Gomez, Skiba, & Snow, 2016; Squires, Macdonald, Culham, & Snow, 2015). It is the case, however, that only real objects offer physical actions. Images of objects, although they imply actions, do not themselves afford physical grasping or interaction. In line with these ideas, a number of recent studies suggest that real objects may be processed or represented differently to their image-based counterparts. For example, real objects are associated with enhanced memory performance (Snow et al., 2014), longer visual exploration in primates (Mustafar et al., 2015) and a lack of neural adaptation as measured by fMRI (Snow et al., 2011).

Leftward spatial attention biases in in healthy observers

In addition to the idea that action affordances might bias attention, data from neuropsychological patients and psychophysical studies in healthy observers show that attention may not be distributed uniformly across the visual field. In severe cases, patients with damage to one cerebral hemisphere can suffer from a neurological a condition known as unilateral visual neglect, in which objects within the side of space opposite the lesioned hemisphere (in the contralesional visual hemifield) fail to reach awareness (Corbetta & Shulman, 2011; Mattingley et al., 2004), and attention is biased towards stimuli and events in the opposite (‘ipsilesional’) visual field (Snow & Mattingley, 2006, 2008). Interestingly, a similar (albeit milder) form of leftward hemispatial neglect is commonly observed in neurologically healthy observers, and is known as ‘pseudoneglect’ (Bowers & Heilman, 1980). Although pseudoneglect has been attributed to the right hemisphere’s dominance in representing visual space (Heilman & Van Den Abell, 1979; Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990), the underlying cognitive and neural mechanisms that give rise to pseudoneglect are currently not well understood (for example see, Benwell, Harvey, & Thut, 2014).

Studies have reported subtle leftward biases in healthy observers using a range of paradigms, including the Grayscales task (Mattingley et al., 2004; Schmitz, Deliens, Mary, Urbain, & Peigneux, 2011), size judgments (Charles, Sahraie, & McGeorge, 2007), and change detection tasks (Iyilikci, Becker, Gunturkun, & Amado, 2010). In the classic Greyscales task, participants are asked to judge which of two left-right mirror-reversed brightness gradients ('greyscales') seems to be darker than the other. The stimuli, which are presented as two bars, one above the other, are shaded from black at one end, to white at the other, with the black and white ends reversed in each bar. Healthy observers typically perceive the bar whose leftward end is black as being darker than the other, even though both stimuli have the same overall contrast (Mattingley et al., 2004). In the size judgment task, (e.g., Charles et al. (2007) participants are presented with circles and ellipses on either the left or right side of the screen and the observers perceived the objects in the left hemifield as being wider than those on the right. Using a change detection task (e.g., Iyilikci et al. (2010) presented computerized moving dots that changed their color either on the left or the right side of the screen. Participants were significantly faster to detect changes on the left versus the right side. Taken together, these results underscore the idea that pseudoneglect reflects a high-level unilateral spatial attentional bias that facilitates processing of stimuli at the attended location.

Classically, however, pseudoneglect has been studied using *line bisection tasks* (Brooks, Darling, Malvaso, & Della Sala, 2016; Jewell & McCourt, 2000; Umilta, Priftis, & Zorzi, 2009). In the visual line bisection task, observers are asked to point manually, or use a computer mouse, to mark the midpoint of a horizontally-presented line (Jewell & McCourt, 2000). Healthy observers tend to mark the line slightly to the left of true center (Jewell & McCourt, 2000). Because a similar visuospatial bias is also seen in other sensory modalities, such as touch (Jewell & McCourt, 2000), this suggests that the effect reflects bias in high-level attention, rather than lower-level sensory deficit. Moreover, the leftward spatial bias in line bisection is exaggerated under conditions where the stimulus is positioned to the left of the observer's midline (Jewell & McCourt, 2000).

Interestingly, leftward biases in the line bisection tasks are modulated by the distance of the stimulus from the observer (Jewell & McCourt, 2000; McCourt & Garlinghouse, 2000; McCourt, Garlinghouse, & Butler, 2001; Sosa, Teder-Salejarvi, & McCourt, 2010). For example, McCourt and Garlinghouse (2001) conducted the line bisection task with two groups of participants; one group performed the task with the stimulus placed within reach in 'peripersonal' space (45 cm), while in the other group the stimulus was positioned 95 cm from the target in 'extrapersonal' space. The authors found that the magnitude of pseudoneglect decreased significantly when the stimulus was in extrapersonal versus peripersonal space. The influence of stimulus distance on pseudoneglect, outlined above, appears to be related specifically to reachability, rather than distance per se. For example, when a stimulus is positioned outside reachable space, but the observer has an elongated tool that extends their 'reachable space' to include the stimulus, the leftward attentional bias returns (Longo & Lourenco, 2006).

In line with the idea that *reachability* may be important in modulating pseudoneglect, the leftward bias in visual attention has been reported frequently in tasks involving real-world tangible objects, and in studies conducted outside the laboratory in naturalistic settings (Benedetto, Pedrotti, Bremond, & Baccino, 2013; Nicholls, Hadgraft, et al., 2010; Nicholls, Loetscher, & Rademacher, 2010; Nicholls, Loftus, Orr, & Barre, 2008). For example, Nicholls et al. (2008) asked their participants to walk through a doorway while texting and most of them bump on their right (neglected) side. In another study it has been observed that participants who navigated an electric wheelchairs collided more frequently with objects on the right side (Nicholls, Hadgraft, et al., 2010). Benedetto et al. (2013) showed that participants involved in a virtual driving task were more attentive to the left side of the road.

The current study

In the current study we examined whether the inherent leftward bias in visuospatial attention (pseudoneglect) is stronger for objects that are graspable, versus those that are not. We used a modified version of the Posner cueing task (Posner et al., 1980) as a sensitive measure of visuospatial attention in neurologically healthy observers. In the Posner task, participants are required to detect a briefly-appearing target that is positioned either end of a centrally-presented cue. To determine the extent to which lateralized effects of attentional capture by the cue was attributable to action affordances, we compared detection performance for real tools, with high-resolution computerized images of the same items. We also compared cueing effects for two classes of objects: tools (which are associated strongly with specific grasping routines) and non-tool fruits and vegetables that are not strongly associated with a specific function or action routine (Skiba & Snow, 2016). In Experiment 1, the stimuli were positioned within reaching distance. In Experiment 2, the experiment was repeated with the stimuli positioned out of reach. We predicted that (1) the leftward attentional bias would be stronger for objects that are physically graspable (i.e., real objects) versus those that are not (computerized images); (2) the leftward bias should be stronger for tools than non-tool fruit/vegetable stimuli; and (3) that any effects of graspability that are observed when the stimuli are within reach should disappear when the same stimuli are positioned out of reach.

Study 1

Methods

Participants

Twenty-five undergraduate students (17 females, mean age = 23.70 and SD = 7.47) from the University of Nevada, Reno participated in Experiment 1 for course credit. All participants reported normal or corrected-to-normal vision and were right-handed as measured by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971). Participants provided written informed consent prior to the experiment, and all experimental procedures were approved by the University of Nevada, Reno Social, Behavioral, and Educational Institutional Review Board.

Stimuli and Apparatus

The stimuli consisted of objects presented in two different ***Display Formats***: real objects and computerized images of the same items. The real object stimuli (the cues) consisted of two ***Object Categories***: six were elongated real tools, and six were non-tool elongated fruit/vegetables (12 objects in total). The tools had a mean horizontal length of 19.9 cm (SD = 3.92). The fruit/vegetable stimuli were matched in mean horizontal length (M = 19.0 cm; SD = 2.34) to the tools (t(10) = 0.456, p = 0.66). The objects were mounted to a 25x15'' sheet of acrylic glass that was cut to match the outer dimensions of a standard 27'' ASUS (VG278HE) LCD monitor. On real object cue trials, the acrylic sheet was attached to the monitor using Velcro tape. The objects were centered at the screen (**Figure 1**). On each trial, the objects were mounted to the vertical and horizontal midpoint of the acrylic sheet using double-sided adhesive tape, which was attached to the rear side of the stimulus (not visible to the participant). Each object could be mounted in one of two ***Cue Orientations*** - with the handle (for the tools) or the stem (for the fruits/vegetables) oriented towards the left, or towards the right side of the display, yielding a total of 24 possible stimulus configurations (2 ***Display Formats*** x 2 ***Object Categories*** x 2 ***Cue Orientations***). Separate (but identical) exemplars of each object were used for each left/right orientation. A square marker displayed on the LCD screen, allowed for accurate and consistent positioning of the stimuli on each real object trial.

Photos of the real object stimuli were taken with a Canon 7D DSLR camera with a 24-70mm f/2.8 lens with a constant f-stop ISO, focal length, and shutter speed. Because the real objects were illuminated both from above, and from behind due to the illumination of the monitor, there were no cast shadows. The resulting color images were resized to match the real objects, and superimposed on a white background (RGB: 255 255 255) using Adobe Photoshop CC. The images (n=24) were matched closely to the real exemplars for size, viewpoint, and illumination. The image cues were displayed on the LCD monitor (without the acrylic glass attached).

The target on each trial was a circular gray dot (RGB: 240 240 240) 50 mm in diameter, presented using the LCD monitor. The target appeared within one of two lateralized placeholders (square boxes, 100x100mm) on the monitor, each centered 0.5 cm from the left and right endpoints of the object. The boxes indicated the potential location of the target. The LCD monitor was controlled by a Windows computer (Intel Core I7-4770 3.4 GHz, operating on 16 GB RAM) supported by a dedicated video card (NVIDIA Quadro K4000). In all trials of Experiment 1, the LCD monitor was positioned at a distance of 57 cm (within grasping distance) and head position was fixed using a chinrest. Viewing time was controlled using computerized LCD goggles on all trials. Headphones (Bose AE2) were used to present audio cues, and to deliver white noise (Mono, 44100 Hz, 32-bit float) in the intertrial interval. We used a remote infrared video-based eye-tracker (RED, SMI, Germany; 60 Hz sampling rate, ~0.03^{o} spatial resolution, 0.4^{o} accuracy) to ensure that subjects' gaze was centered on the fixation point at the start of each trial. The fixation point was a red square (RGB: 255 0 0 0, 0.5x0.5cm) which was displayed (in image format) at the vertical and horizontal midpoint of the LCD monitor. Participants used a standard wired

QWERTY computer keyboard in order to respond to location of the target. A wireless QWERTY keyboard was used by the experimenter to begin each trial. MATLAB (Mathworks, USA) and Psychtoolbox were used to control stimulus presentation and record responses.

Figure 1. Display Setups Experiment 1. The LCD monitor was positioned at 57 cm from the observer. Participants wore noise-cancelling headphones that played white noise. Viewing time was controlled using LCD glasses in both the picture and real object conditions. A chin rest was used to control viewing distance, and to reduce head movements.

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After completing the Edinburgh handedness inventory, participants were seated in front of the monitor with their chin in the chin rest. The SMI RED eye tracker was calibrated using a five-point calibration procedure. Participants began with 10 practice trials, with pictures of objects that were not used in the main experiment. Participants were required to reach a minimum of 80% accuracy on the practice trials before continuing with the main experiment. The trial sequence and timing were identical for both the real object and image conditions.

At the beginning of each trial participants maintained their gaze on a central fixation point (**Figure 2**). Trials would not progress unless participants maintained their gaze on the fixation point for 2000ms. After this time, the PLATO goggles closed for 5000 ms. At the same time, a brief low auditory tone (500 Hz) was emitted via room speakers to cue the experimenter to start preparing the upcoming stimulus (which on real trails involved mounting the object on the the acrylic glass). Next, a second auditory tone (700 Hz) was emitted, and the participants' goggles opened to reveal the stimulus display. The cue (real object or image), and lateralized placeholders, were visible for 800 ms before target onset. The target was displayed for 50 ms. The stimulus and placeholders remained on-screen for a further 400 ms. The LCD goggles closed for a further 3000 ms, during which time the stimuli were removed from the screen (which on real trails involved removing the object from the acrylic glass).

The experiment consisted of four experimental blocks, two for each ***Display Format*** (images versus real objects). The order of blocks in each ***Display Format*** was counterbalanced using a balanced Latin Square Design. For the manipulation of ***Cue Orientation***, in each block, half of the trials depicted the cue with the handle/stem facing to the left, and the remainder to the right. For the manipulation of ***Target Side***, on half of the trials in each ***Display Format***, ***Cue Orientation***, and ***Object Category***, the target appeared at the handle/stem end, and on the remaining trials the target appeared at the head/tip end of the cue. The entire experiment consisted of 96 trials (24 objects x 2 handle/stem orientation configuration x 2 target positions). The order of the trials within each block was randomized, separately for each subject. The entire study took ~1.5 hours to complete.

Participants were told that the central object cue was irrelevant to their task, held no predictive information about target location, and should be ignored. Participants were instructed to respond as quickly and accurately as possible as to whether the target appeared on the left or right side of the display. Participants entered their responses by pressing the Left or Right ‘Shift’ key on the computer keyboard, with either the left or right index finger, respectively. Participants were instructed to maintain their gaze on the fixation point throughout the duration of the trial.

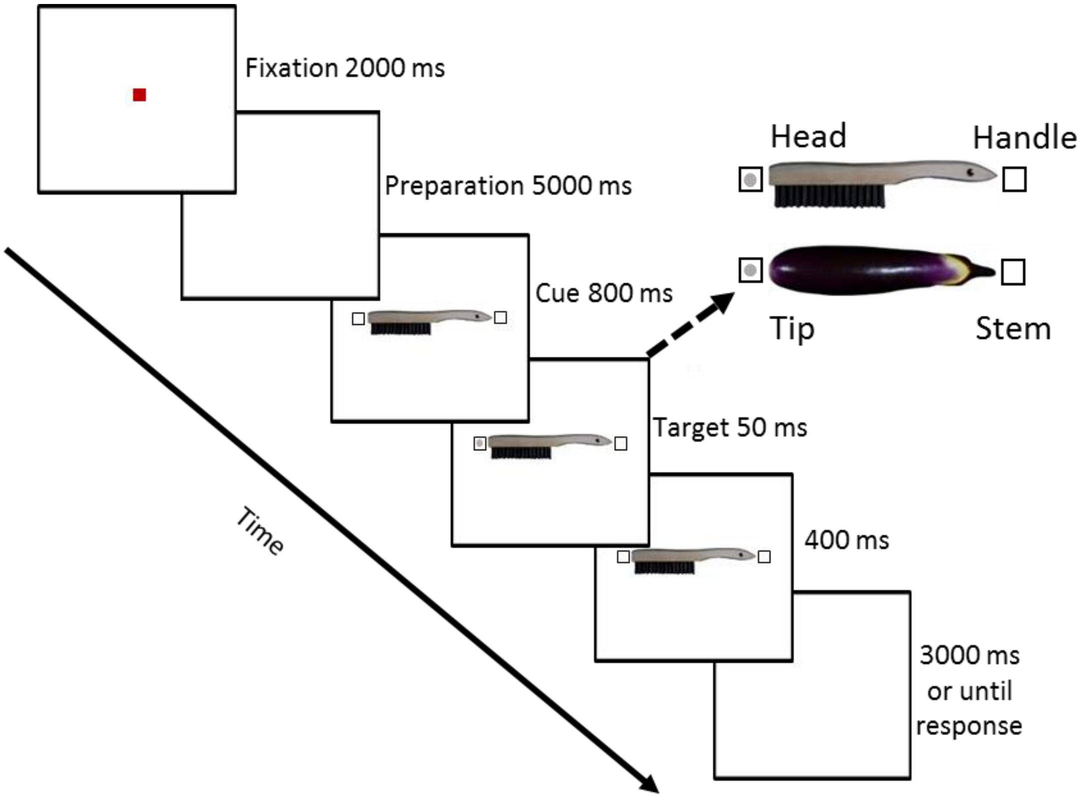


Figure 2. Trial sequence for Experiment 1. Participants first fixated a red fixation point for 2000 ms. Next, a low frequency tone sounded. The PLATO goggles closed (5000 ms) during which time the experimenter prepared the stimulus for the upcoming trial. A subsequent high frequency tone signaled to the subject that the trial was about to start. The LCD glasses then opened, revealing the cue object (real or image) for 800 ms. A target dot then appeared for 50 ms. The cue (object) remained visible for a further 400 ms, after which time the goggles closed. Participants had 3000 ms to enter a button-press response as to whether the target appeared on the left or right side of the cue.

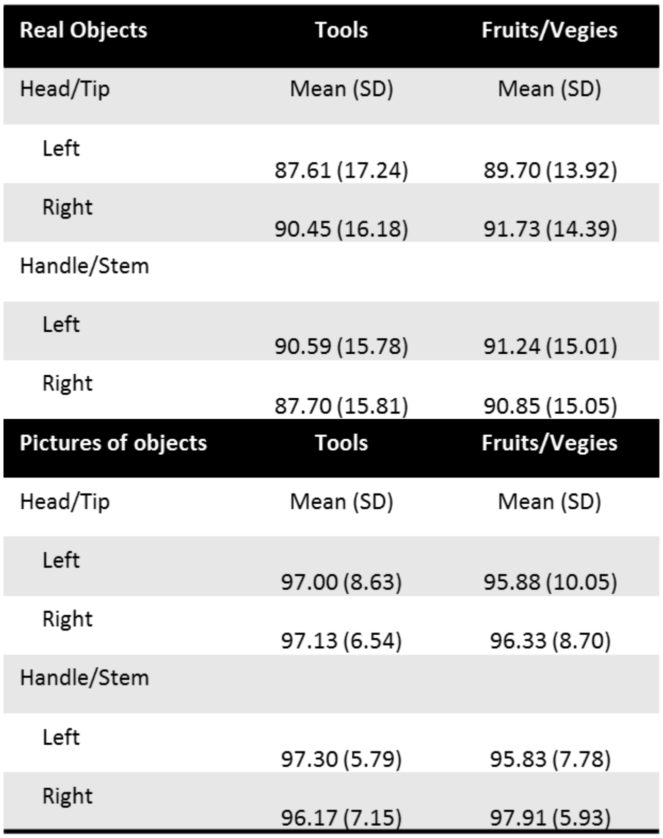
Results

Reaction time (RT) and accuracy (ACC) data were collected from all participants. Only correct trials were included in the RT analyses. Any trials in which RTs were >2.5 standard deviations (SD) from the mean, were removed from the analyses, separately for each participant (14.4 % of all trials). The data were analyzed using a four-way repeated measures Analysis of Variance (RM ANOVA) with the factors of ***Display Format*** (picture vs. real), ***Object Category*** (tool vs. fruit/vegetable), ***Cue Orientation*** (handle/stem left vs. handle/stem right), and ***Target Side*** (handle/stem, head end/tip).

Accuracy

Mean accuracy in each condition is displayed in **Table 1**. The participants performed at a high level of accuracy overall (M = 93.3%). The Repeated Measures ANOVA revealed a main effect of the Display Format (F(1, 24) = 12.510, p = 0.002, ηp2 = 0.343) in which participants were more accurate overall to detect the target in the pictures (M = 96.7%) versus the real object trials (M = 90.7%). There were no other significant main effects or interactions involving accuracy (all p values > 0.176).

Table 1. Mean accuracy in each condition in the first study.



Real Objects	Tools	Fruits/Vegies
Head/Tip	Mean (SD)	Mean (SD)
Left	87.61 (17.24)	89.70 (13.92)
Right	90.45 (16.18)	91.73 (14.39)
Handle/Stem		
Left	90.59 (15.78)	91.24 (15.01)
Right	87.70 (15.81)	90.85 (15.05)
Pictures of objects	**Tools**	**Fruits/Vegies**
Head/Tip	Mean (SD)	Mean (SD)
Left	97.00 (8.63)	95.88 (10.05)
Right	97.13 (6.54)	96.33 (8.70)
Handle/Stem		
Left	97.30 (5.79)	95.83 (7.78)
Right	96.17 (7.15)	97.91 (5.93)

Reaction Time (RT)

In the analysis of RT there was a main effect of ***Display Format*** (F(1, 24) = 4.629, p = 0.042, ηp2 = 0.162) in which participants were faster to respond to the targets in the pictures (M = 601) than the real object trials (M = 624). There was a significant two-way interaction between the ***Cue Orientation*** and ***Target Side*** (F(1, 24) = 0.096, p = 0.006, ηp2 = 0.275), however, this was qualified by a significant 3-way interaction between the ***Display Format***, ***Cue Orientation*** and ***Target Side*** (F(1, 24) = 7.206, p = 0.013, ηp2 = 0.231). This 3-way interaction was decomposed by examining the effect of ***Cue Orientation*** and ***Target Side***, separately for stimuli in each ***Display Format*** using 2-way RM ANOVAs. Mean RTs in each ***Cue Orientation*** and ***Target Side*** condition are displayed in **Figure 3**, separately for trials in each ***Display Format***. There were no significant

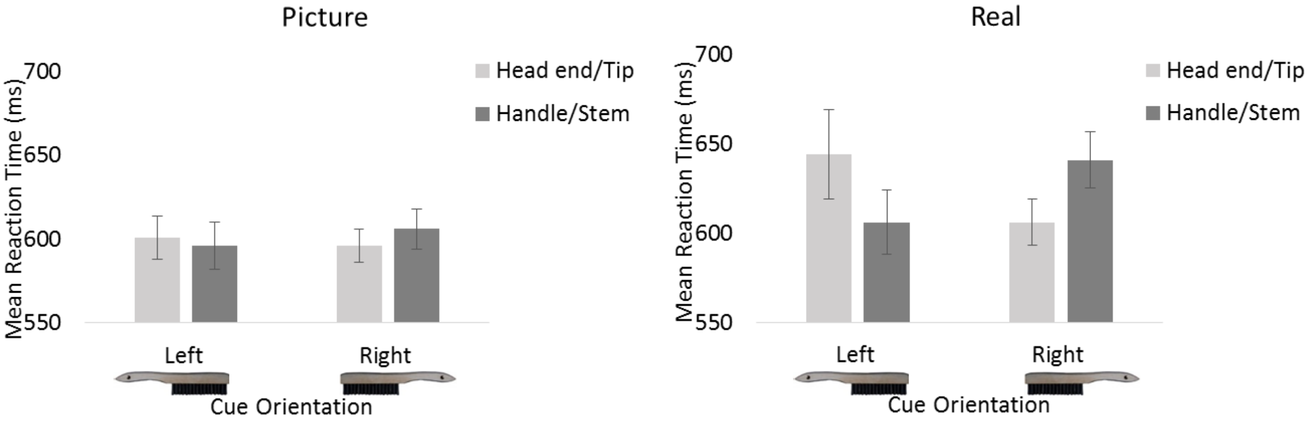
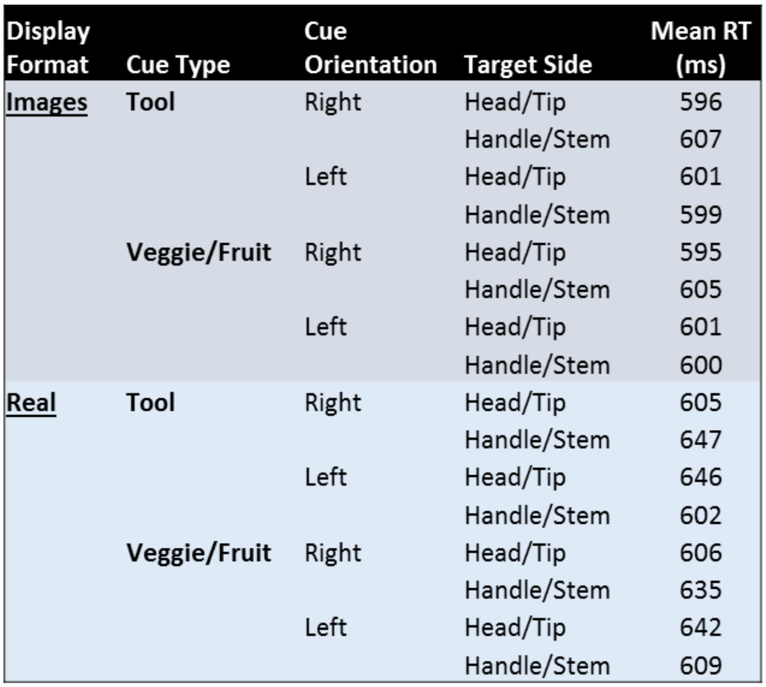


Figure 3. Reaction time performance of the participants in the near distance study plotted as a function of Cue Orientation (left vs. right) and the Target Side (handle/stem vs. head/tip) plotted separately for pictures (on the left) and real objects (on the right). In case of real object participants were always faster when the target appeared on the left side of the display. Error bars here and in the following figures represent +/- 1 standard error of the mean.

differences in RTs on image cue trials. Conversely, for real object trials, there was a significant two-way interaction between ***Cue Orientation*** and ***Target Side*** (F(1,24) = 11.364, p = 0.003, ηp2 = 0.321): when the object's handle/stem was oriented leftward, detection was faster for targets appearing near the handle/stem end, but when the handle/stem was oriented rightward, RTs were faster for targets at the head/tip end (t(24) = 2.843, p = 0.009).

Notably, there were no significant interactions involving ***Cue Type*** (all p values > 0.323), suggesting that attention was distributed equally for tools (with specific grasping routines) and non-tool fruits and vegetables (that are not strongly associated with specific functions or action routines) (see also **Table 2**).

Table 2. Mean reaction time in each condition in the first study.



Display Format	Cue Type	Cue Orientation	Target Side	Mean RT (ms)
Images	**Tool**	Right	Head/Tip	596
			Handle/Stem	607
		Left	Head/Tip	601
			Handle/Stem	599
	Veggie/Fruit	Right	Head/Tip	595
			Handle/Stem	605
		Left	Head/Tip	601
			Handle/Stem	600
Real	**Tool**	Right	Head/Tip	605
			Handle/Stem	647
		Left	Head/Tip	646
			Handle/Stem	602
	Veggie/Fruit	Right	Head/Tip	606
			Handle/Stem	635
		Left	Head/Tip	642
			Handle/Stem	609

Study 2

Methods

Participants

Twenty five right-handed undergraduate students were recruited for Experiment 2 (16 females, mean age = 22.52 and SD = 7.16). The recruitment and consent methods were the same as Study 1.

Stimuli, Apparatus and Procedure

The stimuli, apparatus and procedures were identical to Experiment 1, with the exception that the stimuli were positioned outside of reach (114 cm from the observer).

Results

For the analysis of RTs only corrected trials were included. A 2.5 SD filter was applied to remove outliers below and above the mean RT, separately for trials in each ***Display Format*** (14.4 % of all trials). As in Experiment 1, RT and accuracy data were analyzed using a 4-way RM ANOVA with the within subject factors of ***Display Format*** (picture vs. real), ***Object Category*** (tool vs. fruit/vegetable), ***Cue Orientation*** (handle/stem left vs. handle/stem right), and ***Target Side*** (handle/stem, head end/tip). In addition, the data from Experiments 1 and 2 were contrasted using a 5-way Mixed Model ANOVA, with the additional between-subjects factor of ***Distance*** (near, far). Significant effects were examined using follow up paired-samples t-tests, where appropriate.

Accuracy

Mean accuracy in each condition are displayed in **Table 3**. As in Experiment 1, participants were very accurate (mean = 96.6% correct). A RM ANOVA on the accuracy data revealed a significant main effect of ***Display Format*** (F(1, 24) = 5.963, p = 0.022, ηp2 = 0.199) in which observers were again faster to detect targets with images (M = 99.2%) compared to real object displays (M = 96.6%). There were no other significant main effects or interactions (all p values > 0.226) in the accuracy data.

Table 3. Mean reaction time in each condition in the second study.

Real Objects	**Tools**	**Fruits/Vegies**
Head/Tip	Mean (SD)	Mean (SD)
Left	95.89 (9.46)	96.46 (10.33)
Right	97.04 (7.36)	96.93 (8.44)
Handle/Stem		
Left	96.80 (6.46)	95.20 (13.46)
Right	96.67 (6.11)	97.94 (4.57)
Pictures of objects	**Tools**	**Fruits/Vegies**
Head/Tip	Mean (SD)	Mean (SD)
Left	99.27 (2.55)	98.17 (3.75)
Right	99.33 (2.31)	99.67 (1.67)
Handle/Stem		
Left	98.24 (5.79)	99.30 (2.41)
Right	99.50 (2.50)	100.00 (0.00)

Reaction Time

A RM ANOVA on the RT data revealed no significant main effects. Only two-way interaction between ***Cue Orientation*** and ***Target Side*** was significant (F(1, 24) = 6.32, p = 0.019, ηp2 = 0.208). For rightward oriented handle/stem cues, RTs were at the head/tip end (left targets) (M = 588) than at the handle/stem (M = 598, SEM = 19) (t(24) = -2.049, p = 0.052). Conversely, for leftward oriented when the stimuli were oriented towards left participants were faster to indicate the target location at the handle/stem end (M = 589, SEM = 17) than the head/tip end (M = 600) (t(24) = 2.441, p = 0.022). Therefore, the leftward bias presented in the within reach condition disappeared in the far distance version of the study (see **Figure 4**).

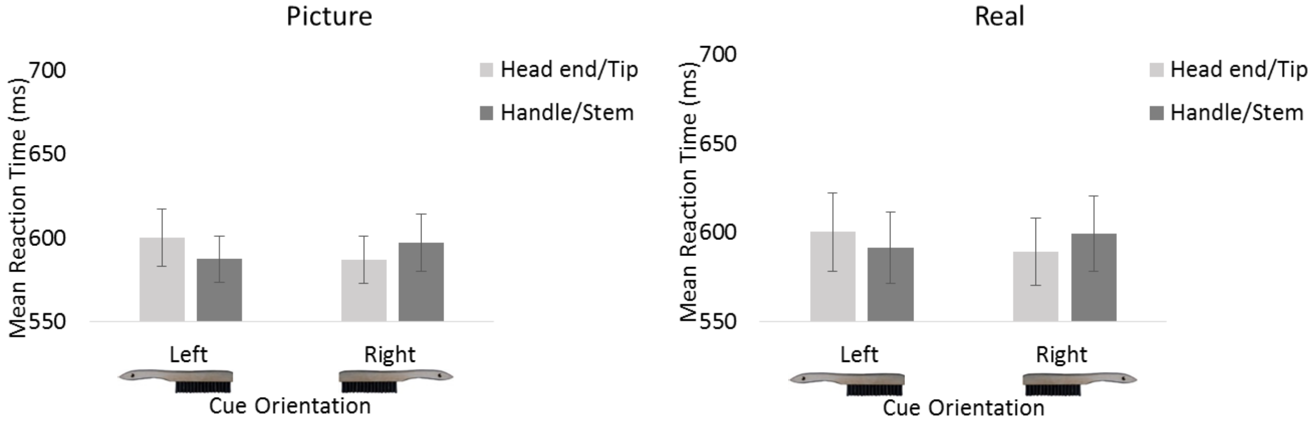


Figure 4. Reaction time performance of the participants in the second study plotted as a function of Cue Orientation (left vs. right) and the Target Side (handle/stem vs. head/tip) plotted separately for pictures (on the left) and real objects (on the right). The leftward bias is not present anymore for real objects displayed in the far distance.

Finally, we used a 5-way mixed-model ANOVA to compare accuracy, and mean RTs, for participants in Experiment 1 (cues within reach) vs. Experiment 2 (cues outside of reach).

For the analysis of accuracy, the RM ANOVA revealed that accuracy was higher in the Far distance (M = 97.3%) than the Near distance (M = 93.3%; F(1, 48) = 6.07, p = 0.017, ηp2 = 0.112). There was also a main effect of ***Display Format*** (F(1, 48) = 18.297, p < 0.001, ηp2 = 0.276) in which observers were more accurate with the picture displays (M = 97.9%) than the real objects (M = 93.3%) There were no other significant main effects or interactions in the accuracy data (all p values > 0.172). The analysis of RTs revealed a significant interaction between the ***Cue Orientation*** and ***Target Location*** (F(1, 48) = 14.988, p < 0.001, ηp2 = 0.238), and a 3-way interaction between Display Format, ***Cue Orientation*** and ***Target Side*** (F(1, 48) = 7.308, p = 0.028, ηp2 = 0.097). These results were qualified by a significant 4-way interaction between ***Display Format***, ***Cue Orientation***, ***Target Location***, and ***Distance***, confirming that the superior performance for left-sided targets was present only for real objects (not images) that were positioned within reach (F(1, 48) = 7.308, p = 0.009, ηp2 = 0.132).

Discussion

A modified version of the Posner cueing task was used to examine whether visuospatial attention differs for real objects versus two-dimensional images of objects. The stimuli were everyday tools, and fruits and vegetables. In the first study participants performed the task in the near distance and the participants' detection performance was better for left-sided targets in the real object displays but not for the images. Therefore, the pseudoneglect was only present when the participants were exposed to the real objects. In the second study the subjects performed the same task with the increased viewing distance so that the real object stimuli were seen in the far distance. Under these conditions, the leftward attentional bias for the real objects disappeared. The results indicate that pseudoneglect depends critically on the tangibility of the stimulus and it is affected by physical affordance provided by real objects.

In our previous study we used the same paradigm as here and established that head end of tool images biases attention and facilitates the participants' response time to a target cued by that part of tools (Skiba & Snow, 2016). Moreover, no differences in our participants' performance were observed for the control stimuli category, that is, fruits and vegetables. Based on that results we hypothesized that when using real objects we should observer faster reaction time in detecting the target cued by handle of tools because of its relevance for grasping and manual interaction. The current data showed a different pattern of results than expected. It seems that having real manipulable and elongated real objects activated the leftward bias of visuospatial attention that was stronger than the bias to the functional part of tools. Moreover, although in this expereiment we had a block of trials with images of tools we could not replicate the results of our previous study (Skiba & Snow, 2016). It is possible that the presence of additional block of real objects influence participants' performance. Also in this study the trails sequence included 5 sec inter-trial interval and the participants were wearing the PALTO goggles. Therefore, there is possibility that the methodological differences between the two study influenced the result. However, there is also a strong possibility that presence of real object altered visuospatial attention towards the left side of the display.

Interestingly, this study showed a similar magnitude of pseudoneglect for real tools and vegetables presented within reach of my participants (near distance study). Tools and Vegetables are familiar and manipulable classes of everyday objects. However, tools have a strong functional specificity and are associated with more standardized form of grasping than vegetables (Skiba & Snow, 2016). It is well know that viewing tools facilities motor responses and it is related to stronger activity in dorsal parietal regions of the human brain (Almeida, Mahon, & Caramazza, 2010). However, as a recent study showed that vegetables are also associated with higher activity in the dorsal stream (Sakuraba, Sakai, Yamanaka, Yokosawa, & Hirayama, 2012). As suggest by Sakuraba et al. (2012) this may be related with the fact that vegetables as tools are elongated and therefore appropriate for grasp. Thus, a possibility for grasping of real objects in the near space seems to be main factor influencing the results of this investigation. In the future studies it would be interesting to verify the current result by using also real stimuli but not graspable such as cactuses.

It should be also pointed out that the possibility for manual interaction with real objects could alert my participants and in a result made them more vigilant and intensified the leftward bias of their attentional system. The evidence for such explanation may come from studies investigating an intensity of pseudoneglect under low and high arousal level (Manly, Dobler, Dodds, & George, 2005; Schmitz et al., 2011). Manly et al. (2005) showed that sleep deprived shift-workers present a reversal of their attentional bias in a landmark task. Smitch et al, (2011) expanded those results and revealed that the leftward bias complete diminish when their participants performed a grayscale task at 5:00 AM and reappeared at 9:00 AM. The authors agreed that cardicadian-related variations in vigilance may affect visuospatial attentional asymmetries. Moreover, the brain imaging studies have revealed that real objects seem to be under constant surveillance of the visual system and therefore the human visual system may be more vigilant in the presence of real objects (Snow et al., 2011; Squires et al., 2015). For example, Snow et al. (2011) showed that real objects are not a subject to repetition suppression effect, that is, a decrement in Blood Oxygenated Level Response after many repetitions of the same stimuli. It is possible then that in this study real objects increased a vigilant state of our participants and therefore their visuospatial attention was unintentionally directed towards left side.

Concluding, participants who performed a modified version of the Posner cueing task showed a bias to the left side of the display when presented with real objects in the near distance (57 cm). In the future studies it would be necessary to verify if non-manipulable objects (for example, flowers) presented in the near distance also produce similar bias. If opposite is true that would suggest that affordance have direct influence on the leftward error in visuospatial orienting.

Experiment 2: Differences in fixations during grasping and categorization tasks with real object, 2D and 3D.

Introduction

Eye movements are influenced by both bottom-up stimulus-driven stimulus properties (Itti & Koch, 2000) and top-down control mechanisms that guide behavior in accordance with an observers' current goals and intentions (Kowler, 2011; Land, 2006; Orquin & Mueller Loose, 2013). Although, there is a growing literature about eye movements in real-world environments (Hayhoe & Ballard, 2005; Kretch & Adolph, 2015) our current understanding of oculomotor patterns during object exploration and interaction is based overwhelmingly on computerized (pictorial) displays of objects and scenes (Castelhano, Mack, & Henderson, 2009; Henderson, 2003; Henderson et al., 2003). Compared to 2D images, real objects possess additional stereo cues (Loftus, Servos, Goodale, Mendarozqueta, & Mon-Williams, 2004), they have a definite size, distance, location, texture and compliance (Cant & Goodale, 2011; Humphrey, Goodale, Jakobson, & Servos, 1994), and perhaps most importantly they offer genuine physical affordances -the potential for manual interaction (Gibson, 1979).

Eye movements during object scanning and grasping

Previous studies that have examined how humans visually explore simple 2D and 3D shapes, have found that observers typically begin to fixate such objects from their center – a region that is typically referred to as the 'Center of Mass' (COM) of the object (Kowler, 2011; Vishwanath & Kowler, 2004). Similar results have been found for studies examining eye movements to images of objects in the context of computerized naturalistic scenes (Foulsham & Kingstone, 2013; Henderson et al., 2003). However, this pattern of centrally located gaze patterns varies with the subject's task. For example, Drewes, Trommershauser, and Gegenfurtner (2011) used an object identification task that required participant to localize particular animal in a scene; under these instructions, participants were first looking at the head of their target. van der Linden, Mathot, and Vitu (2015) asked their participants to categorize images of single tools as belonging to the kitchen or garage and although their initial saccades were directed towards the COM of objects, the following saccades were directed toward a head end of the object (e.g., a blade of a knife). In one of our previous studies conducted in our laboratory, we also found the initial fixation was directed towards center of a tool but subsequent fixation was directed towards head end of tools (Skiba, Papa, & Snow, *manuscript in preparation*). Therefore, these studies showed that although objects are initially explored from their physical center, later attention is directed towards the most relevant part of the object depending on the task.

A number of studies has shown that eye movements are influenced by observers' current action goals (Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2011; Land, 2006; Land & Hayhoe, 2001). For example, in a study by Desanghere and Marotta (2011) participants were asked to preform two tasks, one required them to point towards a simple box-like shape, and the other required them to grasp the box at its edges. In the pointing task, fixations were focused on the center of the object, however, in the grasping task fixations were concentrated at top edge of the cube at the upcoming point of contact by the fingers. Similarly, Brouwer, Franz, and Gegenfurtner (2009) pointed out that depending on the task our eye movements adjust to guide motor action. In their study they asked participants to perform grasping and viewing of real simple shapes (e.g., squares, crosses, triangles) attached to a Plexiglas screen mounted on a computer monitor. In both task the initial fixations and saccades were directed towards the object's center of mass. However, in the grasping task, subsequent saccades were landing at places difficult to grasp that required more attention to prepare an appropriate grasp. Therefore, when interacting with objects eye movements may be important for guiding motor actions (Land and Hayhoe (2001).

Objects affordance and eye movements

This leaves open the question, however, of whether real familiar objects that offer physical affordances (such as tools) have any special influence on the patterns of eye movements. Gibson (1979) originally coined the term 'affordance' to describe the features of objects that allow an able-bodied observer to perform an action with the object. Pictures of manipulable objects attract attention more so than images of non-manipulable objects (Garrido-Vasquez & Schubo, 2014; Handy et al., 2003). Given that eye movements can be tightly linked to attention, it is possible that eye movements will be directed preferentially to those parts of objects that afford interaction –such as handles (Myachykov, Ellis, Cangelosi, & Fischer, 2013). However, the studies that have examined eye movements to tools were conducted using computerized images of objects, which do not possess genuine affordances, as do real manipulable objects

Only one study to date has compared directly how eye movements differ between real object displays and 2D images. Mustafar, De Luna, and Rainer (2015) conducted their experiments in primates that were presented with either real blocks or their image displays. The authors observed longer saccades in case of real objects than images of objects. Other studies on human subjects have shown that there are differences in perception of real objects and images that are reflected in the enhanced memory performance for real objects (Snow et al., 2014) or a lack of priming effect or adaption suppression effects measured by fMRI (Snow et al., 2011). Unlike two-dimensional (2D) images, real objects, possess additional three-dimensional (3D) shape cues (Chainay & Humphreys, 2001), they also vary in their surface texture and compliance (Cant & Goodale, 2011), and they have a definite size, weight, distance and location relative to the observer (Konkle & Oliva, 2011). Although, it is difficult to match a 2D image to a real object based on the discussed perceptual differences, the modern technology allows us to present images of object in real color and size and importantly in very vivid 3D space. Previous research have explored 2D and 3D shapes and noted that those are explored similarly (Vishwanath & Kowler, 2004), however, no study so far compared the 3D images to real objects in a motor task. Stereoscopic depth cues are crucial for development of a sensorimotor plan when interaction with objects in a periperesonal space (Holmes & Spence, 2004). Therefore, it is possible that computerized images of objects possessing stereoscopic depth cues will be explored similarly as real objects when asked to grasp them.

The current study

The aim of the current study is to examine whether there are differences in the way healthy human observers fixate real objects and their pictorial representations. Taking into consideration that eye movements are affected not just bottom-up features but also by top-down motor plans and task instruction (Orquin & Mueller Loose, 2013), the participants in this study were asked to perform two tasks. The first *Categorization* task required them to categorize objects as belonging to kitchen or garage; the second *Grasping* task involved physically grasping the objects (or pantomiming the grasp in the case of 2D and 3D stereo images). Critically, participants performed the two tasks with tools displayed in three different display formats: real tools, 3D stereoscopic presentations and 2D planar images. We predicted that the format in which an object is displayed will influence gaze patterns: gaze will be directed towards either the COM, or the head end of tools when they appear as 2D or 3D images (which facilitates object identification), but more towards the handle of real objects. Moreover, these differential effects of display format should be more apparent in the grasping task than the categorization task.

Method

Participants

Thirty undergraduate students (thirteen female, mean age = 26.7 and SD = 6.5) from the University of Nevada, Reno participated in the Experiment for course credit. All participants reported normal or corrected-to-normal vision and were right-handed as measured by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971). Participants provided written informed consent prior to the experiment, and all study procedures were approved by the University of Nevada, Reno Social, Behavioral, and Educational Institutional Review Board.

Stimuli and Apparatus

We compared eye-movements to tools presented in three different **Display Formats**: 2D-images, 3D-stereo images, and real objects. The real object stimuli consisted of ten tools: five of the items were graspable objects typically found in the garage (e.g., hand shovel, wire brush), and the remaining five were kitchen items (e.g. ice-cream scoop, spatula). The tools ranged in length from 3.5 cm to 7 cm and vertical extent from 18 cm - 30.5 cm. Each object was attached to a black foam-core board (63.5 cm, 33.02 cm). The boards were mounted on the lower portion of a 27” monitor (described below), so that the top ~1” of the monitor screen remained visible to the participant (revealing a computerized fixation cross). The tools were attached to the vertical and horizontal midpoint of each board with the handle oriented rightwards, facing the dominant hand. The boards were held in place using black wooden holders attached to the outer frame of the monitor (**Figure 5**). Critically, to ensure that the stimuli appeared in the same position from one trial to the next (thereby matching the image conditions described below), alignment of the boards was fine-tuned using markers on the base and sides of the monitor. Stimulus viewing time was controlled using PLATO liquid crystal occlusion glasses (Translucent Technologies, Toronto, Canada) that alternated between opaque (closed) and transparent states (open) (see **Figure 5c**). The stimuli were illuminated using a set of six custom-built 'super-bright' white computer-controlled LED lights, mounted to the ceiling of the testing room (see **Figure 5b**).

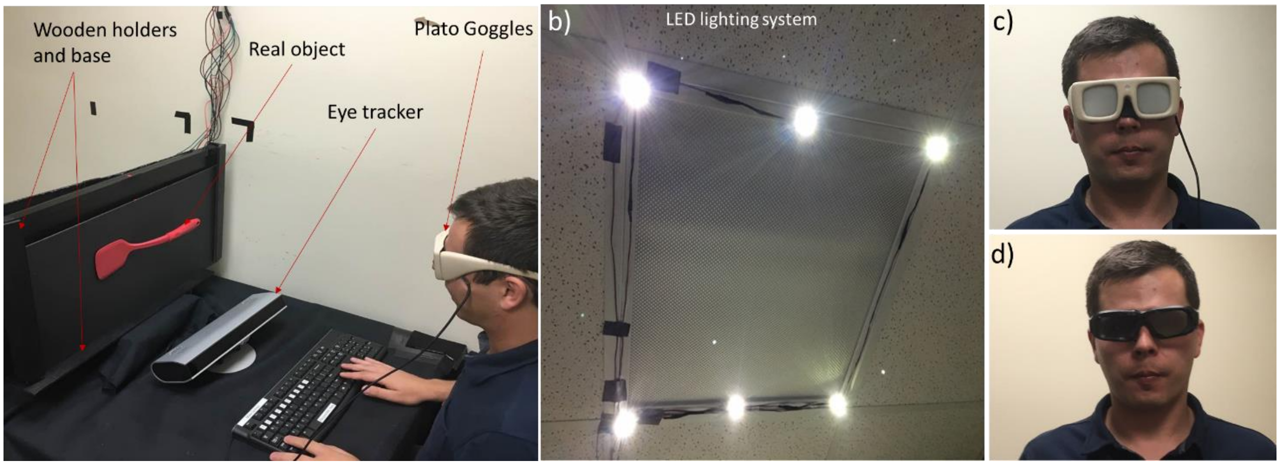


Figure 5. a) Experimental setup for the real object condition. A participant sitting in front of a real object display. The stimulus is mounted on the LCD monitor on black foam core. The foam core board is held in place behind wooden holders mounted on either side of the monitor. At the beginning of a trial the room is completely dark. The participant fixates a red fixation cross located above the board for 1 sec (monitored via the eye tracker), to trigger the LED lighting system (see **b)**, which subsequently illuminates the stimulus. **c)** The Plato goggles prevent the subject from seeing the experimenter changing the stimuli during the ITI. **d)** In 3D viewing condition participants wear Nvidia 3D Vision 2 Wireless Glasses.

To create 2D images of the real objects, we photographed each tool while mounted on the monitor, using identical illumination conditions. The photos were taken from 'straight ahead' at chin height, using a Canon 7D DSLR camera mounted on a tripod. The photographs were taken with a 24-70mm f/2.8 lens with constant F-stop, ISO, focal length, and shutter speed. The resulting high-resolution images were resized to match the real objects using Adobe Photoshop. The 2D images matched the real objects closely for retinal size, position, orientation, background, and illumination, and included cast shadows.

To create the 3D stereo images, the real tools were photographed as described above except that *two* images were taken using a forwards-facing camera positioned 63 mm to the left, and 63 mm to the right, of midline. The left/right viewpoint images were displayed in rapid alternation to observers' left and right eyes, respectively, using active shutter glasses (3D Vision 2, NVIDIA, USA) (see **Figure 5d**) thereby creating the percept of a 3D object. The 2D and 3D images were displayed on a 27" ASUS (VG278HE) LCD monitor (144 Hz) with a screen resolution of 1920 x 1080 pixels. To ensure that stimuli were viewed through glasses in *all* viewing conditions, participants wore the PLATO glasses during the 2D image trials.

The fixation point was a red cross (2^{o} VA) centered at the upper middle of the LCD screen, and was visible in all Display Format conditions. Participants' gaze was monitored on all trials using a remote infrared eye-tracker (RED, SMI, Germany) with 60 Hz sampling rate, ~0.03° spatial resolution, and 0.4^{o} accuracy. The eye tracker was calibrated using a five-point calibration procedure at the beginning of the experiment. Participants used a standard wired QWERTY computer keyboard to make button-press responses in the ***categorization task***. Stimulus presentation, timing, and recording of button-press responses, was controlled using MATLAB (Mathworks, USA) and Psychtoolbox (Brainard, 1997). Data analysis was conducted using BeGaze software (SMI), and IBM SPSS. The Edinburgh Handedness Inventory (Oldfield, 1971) was used as a measure of handedness.

Procedure

Participants performed two ***Response Tasks***: a ***categorization*** task, and a ***grasping*** task. Importantly, the stimulus sequence was identical on all trials; only the nature of the participants' response differed in each task. At the start of each trial, the testing room was dark and a red fixation cross was only source of illumination (**Figure 6a**). The stimulus was not displayed until participants had maintained their gaze for 1000 ms, within an area of 2.5 ^{o} VA diameter around the fixation cross. After this time, the LED room lights turned on, and the stimulus was visible for 3 sec. In the real object and 2D image conditions, the stimulus was revealed by switching the PLATO goggles from the *closed* to the *open* state; in the 3D condition the stimulus was displayed via the active shutter glasses. The intertrial interval (ITI) was 5 sec. During the ITI, the computer screen went black, and in the real object and 2D image trials the PLATO goggles returned to the *closed* state. Participants performed their response as soon as the stimulus appeared.

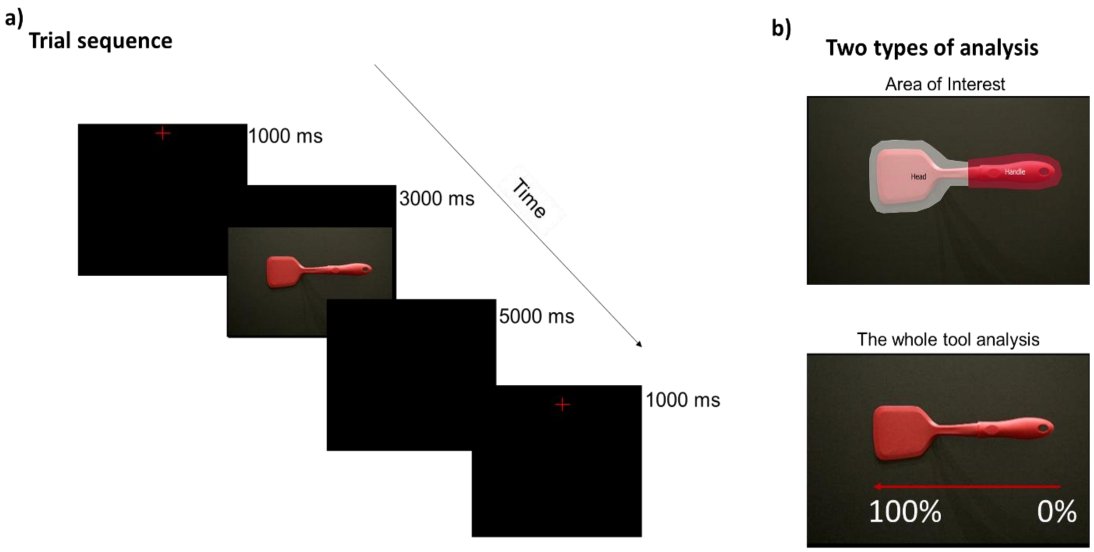


Figure 6. a) Trial sequence of the experiment 1 for both real and picture and 3D display type conditions. At the beginning of the trial participants fixate at the red fixation cross located at the top center of the computer monitor for one second. Next in the real object condition the LED system turns on and participants are presented with an object for 3 seconds. The item is either manually grasped or categorized using a keyboard. In the image and 3D conditions an object is displayed on the computer monitor. After that the goggles close or participants see a black screen (3D viewing condition) and an experimenter prepares a real object on the screen and wait 5 second before the start of the next trial. **b)** In the upper panel: examples of areas of interest (AOI) drawn for head end and handles of tools. In the lower panel: an example of stimulus with marked horizontal tool length used in the whole tool analysis.

The grasping and categorization tasks were completed in separate blocks. In the ***categorization task*** participants made a speeded two-alternative forced-choice decision as to whether the stimulus was an object that would typically be found in the kitchen, or the garage. In the ***grasping task***, participants reached out with the right hand to grasp the object (real object trials), or pantomime a grasp (2D and 3D stereo trials) as if to use the object according to its main function. The trials in each ***Response Task*** (categorization, grasping) and ***Display Format*** (2D, 3D, real) together yielded a total of 6 conditions, each of which were presented in separate blocks. Each stimulus exemplar (n=10) was presented once per block, and the order of trials was randomized within each block. Block order was counterbalanced between subjects using a Balanced Latin Square Design. All participants completed two repetitions of each condition (12 blocks, 120 trials in total), except for six observers who completed each condition only once (6 blocks, 60 trials). The entire experiment took ~2 hours to complete.

At the beginning of the experiment, participants were seated approx. 50-60 cm (within reaching distance) from the computer monitor. Participants were asked to reach out and touch a (real) test object that was mounted on the screen with the right hand. The test object (a wooden spoon) was not used in the main experiment. After calibrating the eye tracker, the experimenter explained the procedure for the ***categorization*** and ***grasping*** tasks. In the ***grasping task***, participants were instructed to reach out and 'grasp' the test object as naturally as possible, as soon as it appeared on the display. Grasping trials were practiced with 2D, 3D and real displays prior to the main experiment. On real object trials, participants were instructed to grasp the handle of the object that was mounted on the display board. On 2D and 3D image trials, participants were told to reach towards the stimulus and pantomime the type of grasp that *would* be required to use the tool according to its main function, if it were physically present. Participants were instructed to start each trial with both hands resting flat on the table in front of them. Participant were told that they had 3 sec from the time the stimulus appeared, to perform their grasp, and to return their hands to the starting position after the grasp was completed. In the ***categorization task*** participants were instructed to decide as quickly as possible whether the stimulus on each trial was one that was typically found in the kitchen, or the garage. Responses on the ***categorization task*** were made using the left and right ‘Shift’ keys using the left and right index fingers, respectively. Participants were advised that they had three seconds to make a response in the categorization task.

Data Analysis

Data from 29 participants were analyzed, except for one participant whose data were discarded due to difficulty obtaining a reliable signal from the eye tracker. Data from the left eye were used for all analyses, although the data were consistent with those from the right eye.

AOI Analysis

Eye-movement patterns were examined within two pre-defined ***Areas Of Interest*** (**AOI**) within each tool: the ‘handle’ and the ‘head’ end. The ‘handle’ was operationally defined as the region used to grasp to use the tool in accordance with its typical function (**Figure 6b** *upper panel*). The ‘head’ end was defined as the part of a tool that is used to interact with other object(s) and/or surface(s). The border between the two AOI was positioned at the physical center of each object. Furthermore, when demarcating the AOI for each tool, a margin of 100 pixels was added to the outer border of each object to ensure that fixations close to the edge were included in the analysis. Importantly, an independent samples t-test confirmed that the mean size (measured in number of pixels) of the head end AOIs (M =

44568.00 SD = 23920.11) did not differ significantly from those of the handle AOIs (M = 414574.14, SD = 16671.98); t (56) =0.528, p = 0.609).

The eye-movement data were analyzed using SMI BeGaze analysis software. Using BeGaze defaults, a fixation is defined as a gaze position that does not extend outside a radius of 100 pixels, for a minimum duration of 80 ms. For each subject, we examined **initial fixations** upon the stimulus, as measured by Entry Time (ET) and First Fixation Duration (FFD). ET was defined as the time elapsed (in ms) between stimulus onset and the start of the first fixation inside an AOI. FFD was defined as the time (in ms) from the start to end of the first fixation inside each AOI. Next, we examined **fixation patterns across the entire trial**, as measured by Fixation Count (FC). FC was defined as the total number of fixations within an AOI across the whole trial. These dependent measures for each observer were combined to produce group averages in each condition. The group data were analyzed using a 3x2x2 Repeated Measures (RM) ANOVA with the factors of Display Format (2D, 3D, real), Response Task (categorization, grasping) and AOI (head, handle). Follow-up paired-samples t-tests were used to break down significant effects, where appropriate.

Whole Tool Analysis

In addition to the AOI analysis, we examined the position of most frequent gaze within the whole tool (without pre-defined AOIs). First, the position of most frequent gaze in x-

(horizontal) co-ordinates was represented visually as a 'heat map', where warmer colors represent the positions of most frequent gaze averaged across observers (see **Figure 10**). Next, we quantified and contrasted these average fixation patterns. Because the 10 objects differed in length, x-axis fixation data for each tool were normalized. For each stimulus, the position of peak fixation was divided by the tool's total horizontal length, where 0% = tip of the handle and 100% = tip of head end (see **Figure 6b** *lower panel*). These data were then averaged across all tools to yield *mean position of peak fixation as a % of tool length*. Finally, we compared mean gaze position in each ***Display Format*** and ***Response Task*** using RM ANOVA. We also further explored the differences in location of the most frequent fixations between the two tasks in each ***Display Format*** using a series of repeated measures t-tests. We also contrasted mean gaze position against the mean horizontal COM of the tool images. The COM of each stimulus was measured as the horizontal centroid of the target image (as a planar surface), as in previous studies (e.g., Brouwer, Franz & Gegenfurtner 2009).

Results

AOI Analysis

Initial fixations

ET

The results of the RM ANOVA on the mean ET data are displayed in **Table 4**. There was a significant main effect of ***Display Format*** ($F(2, 56) = 13.200$, $p < 0.001$, $\eta p2 = 0.320$):

ET was faster for the 2D images (M = 677 ms) compared to the 3D images (M = 889 ms; t(28) = -4.002, $p < 0.001$) and real objects (M = 821 ms; t(28) = -3.786, $p < 0.001$) –possibly attributable to subtle inconsistencies between the AOI boundaries between the 2D images (upon which the AOIs were drawn for the purpose of analysis) versus the 3D and real object trials (see also – heat maps in **Figure 10**). There was also a significant main effect of ***Response Task*** (F(1, 28) = 21.847, $p < 0.001$, ηp2 = 0.438), and ***AOI*** (F(1, 28) = 44.448, $p < 0.001$, ηp2 = 0.614), however, these effects were qualified by a significant ***Response Task*** x ***AOI*** interaction (F(1, 28) = 100.032, $p < 0.001$, ηp2 = 0.781). **Figure 7a** displays mean ET into the handle versus head AOIs of the tools, separately for the categorization and grasping tasks. Follow-up paired-samples t-tests confirmed that participants looked first at the head end of the tool (vs. the handle) in the categorization task (t(28) = -9.723, $p < 0.001$), whereas Entry Time to the head vs. handle were comparable in the grasping task (t(28) = -0.813, p = 423). Interestingly, there was a marginal three way interaction between ***Display Format*** and ***Response Task*** and ***AOI*** (F(2, 56) = 2.858, p = 0.066, ηp2 = 0.093). In Figure 4b the mean Entry Time is plotted separately for each ***AOI*** and in each ***Display Format*** separately for the grasping and categorization tasks. The figure shows that in the categorization task participants were faster to look at the head end AOI rather than the handle across all display types. However, in the grasping task the handle AOI was entered faster only in the case of real tools.

Table 4. A complete set of RM ANOVA results for ET

RM ANOVA ET	df	F-value	p-value (ηp2)
Display Format (D)	**2, 56**	**13.200**	**> 0.001 (0.320)**
Area of Interest (A)	**1, 28**	**44.448**	**> 0.001 (0.614)**
Task (T)	**1, 28**	**21.847**	**> 0.001 (0.438)**
D x A	2,56	0.430	0.653 (0.015)
D x T	2, 56	0.249	0.780 (0.009)
A x T	**1, 28**	**100.032**	**> 0.001 (0.781)**
D x A x T	2, 56	2.858	0.066 (0.093)

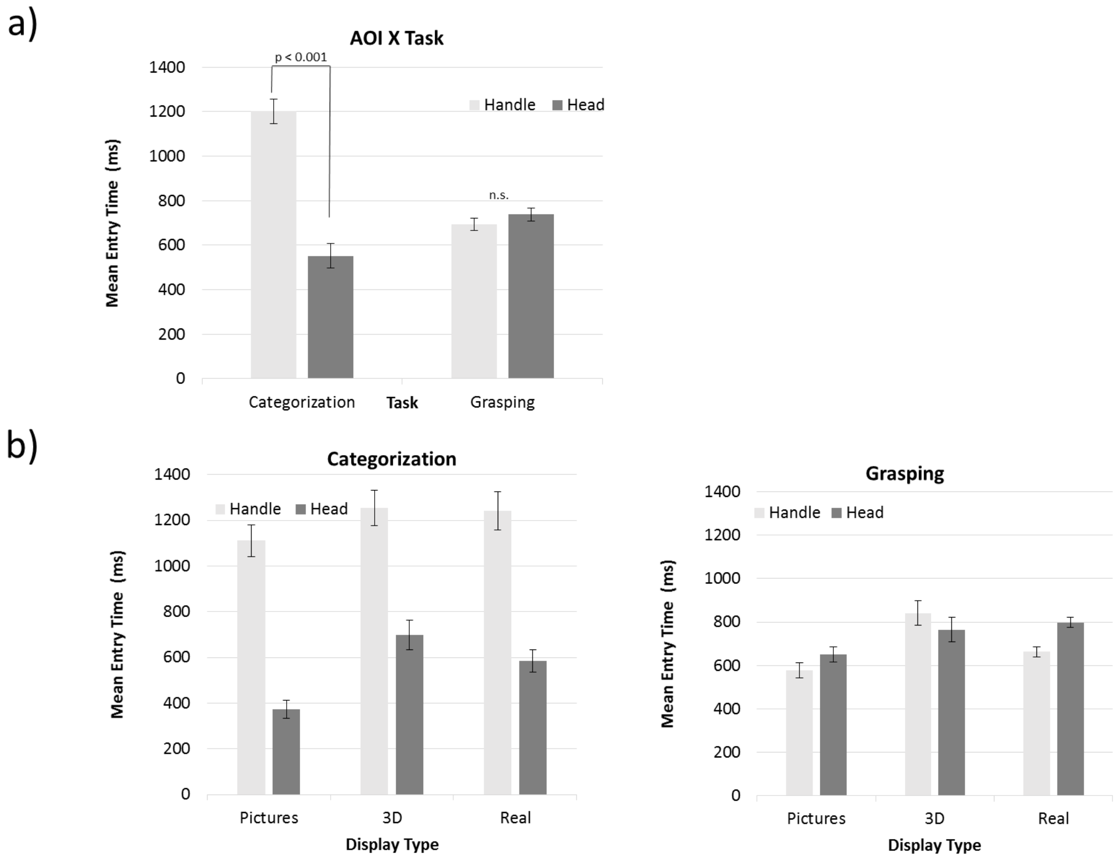


Figure 7. a) Mean Entry Time to each area of interest (AOI) for the categorization and grasping task. The difference between the two AOI is only significant for categorization task ($p < 0.001$). **b)** Mean Entry Times to each AOI (head end and handle) for each Display Format (pictures, 3D, and real objects) plotted separately for the categorization task (on the left) and the grasping task (on the right).

FFD

The results of the RM ANOVA on the mean ET data are displayed in **Table 5**. There was a significant main effect of ***Display Format*** (F(2, 56) = 15.360, p < 0.001, ηp2 = 0.454); FFD was longer for 2D images (M = 259 ms) versus both 3D images (M = 193 ms; t(28) = 6.356, p < 0.001) and real objects (M = 221 ms; t(28) = 3.248, p = 0.004), and the FFD was longer for real objects in comparison to 3D images (t(28) = -3.188, p = 0.007). There was a main effect of ***Response Task*** (F(1,28) = 26.105, p < 0.001, ηp2 = 0.482) in which FFD was longer in the categorization (M = 248 ms) than the grasping task (M = 205 ms). Critically, we found a significant two-way interaction between ***AOI*** and ***Task*** (F(1, 28) = 9.034, p = 0.006, ηp2 = 0.244). **Figure 8** presents mean FFD into the handle versus the head AOI, separately for the grasping and categorization tasks. When the participants were asked to grasp a stimulus they initially fixated longer at the handle rather than the head (t(28) = 4.893, p < 0.001) and they spend similar amount time deploying first fixations between the two AOI when performing the categorization task (t(28) = -0.406, p = 0.691). There were no more significant interactions for this measure of eye movements (all p values > 0.106).

Table 5. A complete set of RM ANOVA results for FFD

RM ANOVA FFD	df	F-value	p-value (ηp2)
Display Format (D)	**2, 56**	**15.360**	**> 0.001 (0.354)**
Area of Interest (A)	1, 28	1.259	0.271 (0.043)
Task (T)	**1, 28**	**31.024**	**> 0.001 (0.526)**
D x A	2,56	2.332	0.106 (0.077)
D x T	2, 56	1.098	0.340 (0.038)
A x T	**1, 28**	**8.958**	**0.006 (0.242)**
D x A x T	2, 56	0.216	0.806 (0.008)

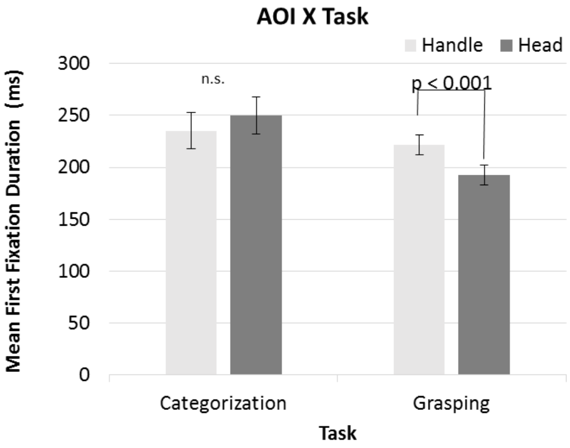


Figure 8. Mean First Fixation Duration time in each AOI (head end and handle) for the categorization task (on the left) and the grasping task (on the right). Participants' first fixation duration was longer for the handle rather than the head end AOI in case of grasping task ($p < 0.001$)

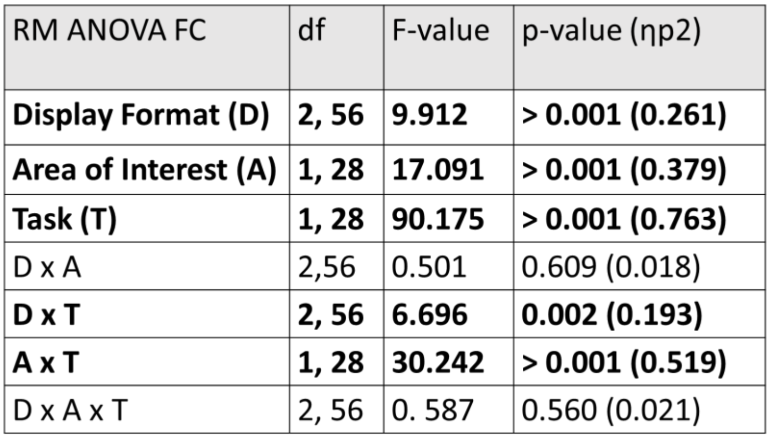
In summary, the initial trial analysis showed that in the categorization task, initial fixations were directed to the head end of the tool (rather than the handle), with no differences towards either end in the grasping task. The duration of initial fixations was longer, however, at the handle of the tools versus the head end in the grasping task, with no differences in fixation duration at the head vs. handle in the categorization task. Notably, however, display format did not influence initial fixations, or their duration, in either task.

The whole trial analysis

FC

The results of the RM ANOVA on the mean FC data are displayed in **Table 6.** There was a main effect of ***Display Format*** ($F(2, 56) = 9.912$, $p < 0.001$, $\eta p2 = 0.261$). Participants made more fixations when exploring the 2D images ($M= 3.73$) than 3D images ($M = 3.171$; $t(28) = 3.459$, $p = 0.001$), and real objects ($M = 3.062$; $t(28) = 3.539$, $p = 0.001$). There were no differences between the number of fixations towards the 3D stereo displays and the real objects (t(28) = -0.067, p = 0.923). There was also a main effect of ***AOI*** (F(1, 28) = 17.091, p < 0.001, ηp2 = 0.379) in which there were more fixations within the tool head (M = 3.733) than the handle (M = 2.909). There was also a main effect of ***Response Task*** (F(1, 28) = 90.175, p < 0.001, ηp2 = 0.763). Observers made more fixations in the categorization task (M = 3.877) than the grasping task (M = 2.765).

Table 6. A complete set of RM ANOVA results for FC



RM ANOVA FC	df	F-value	p-value (ηp2)
Display Format (D)	**2, 56**	**9.912**	**> 0.001 (0.261)**
Area of Interest (A)	**1, 28**	**17.091**	**> 0.001 (0.379)**
Task (T)	**1, 28**	**90.175**	**> 0.001 (0.763)**
D x A	2,56	0.501	0.609 (0.018)
D x T	**2, 56**	**6.696**	**0.002 (0.193)**
A x T	**1, 28**	**30.242**	**> 0.001 (0.519)**
D x A x T	2, 56	0. 587	0.560 (0.021)

These effects were qualified by a significant interaction between ***Display Format*** and ***Response Task*** (F(2, 56) = 6.696, p = 0.002, ηp2 = 0.193). As can been seen in **Figure 9a** observers performed more fixations in the categorization task than in the grasping task in each Display Format. The repeated measures t-test revealed that the difference between the two task was significant for 2D images (t(28) = 2.54, p = 0.02), 3D images (t(28) = 5.023, p < 0.001) and real objects (t(28) = 5.132, p < 0.001). In order to understand what drives the two-way interaction the difference scores between two tasks were computed for each level of ***Display Format*** and compared using a repeated measures t-test (See **Figure 9b**).

The analysis revealed that the 2D images significantly differed in the number of fixation in both task from both 3D displays (t(28) = 2.558,p = 0.016) and real objects (t(28) = 3.878,p = 0.001) but the participants performed similar amount of fixations when presented with 3D displays and real objects (t(28) = 1.251, p = 0.221). Finally, we found a significant interaction between ***AOI*** and ***Task*** (F(1, 28) = 30.242, p < 0.001, ηp2 = 0.519). As can be seen in **Figure 9c** observers performed more fixations in the head than the handle during the categorization task (t(28) = -4.156, p < 0.001) and there were no differences between the two AOIs in the grasping task (t(28) = -.897, p = 0.458).

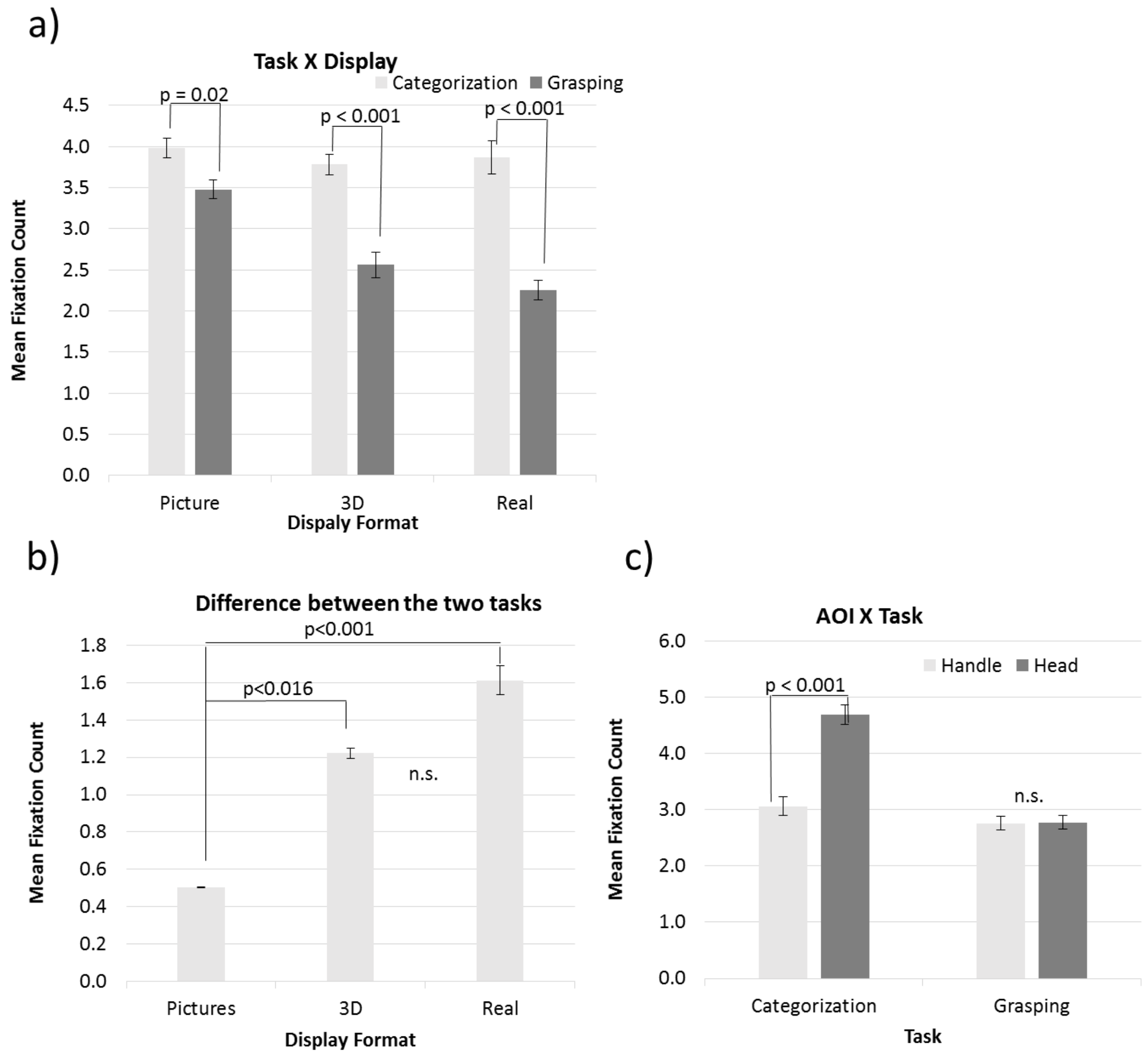


Figure 9. **a)** Mean number of fixations in each task for each Display Format. **b)** Mean fixation count calculated as a difference score between the two task presented for each Display Format. **c)** Mean fixation count between the two AOI (head end and handle) for each task.

Whole Tool Analysis

Heat maps

The data from the whole trials were presented using heat maps on which denser regions, and warmer colors, represent a greater number of fixations, and longer durations of fixations, respectively. The heat maps of all items used in the study in each ***Response Task*** and ***Display Format*** are presented in **Figure 10.** Qualitative inspection of the heat maps shows that participants similarly inspected images, 3D displays and real objects in both categorization and grasping tasks. In the categorization task fixations were focused on the

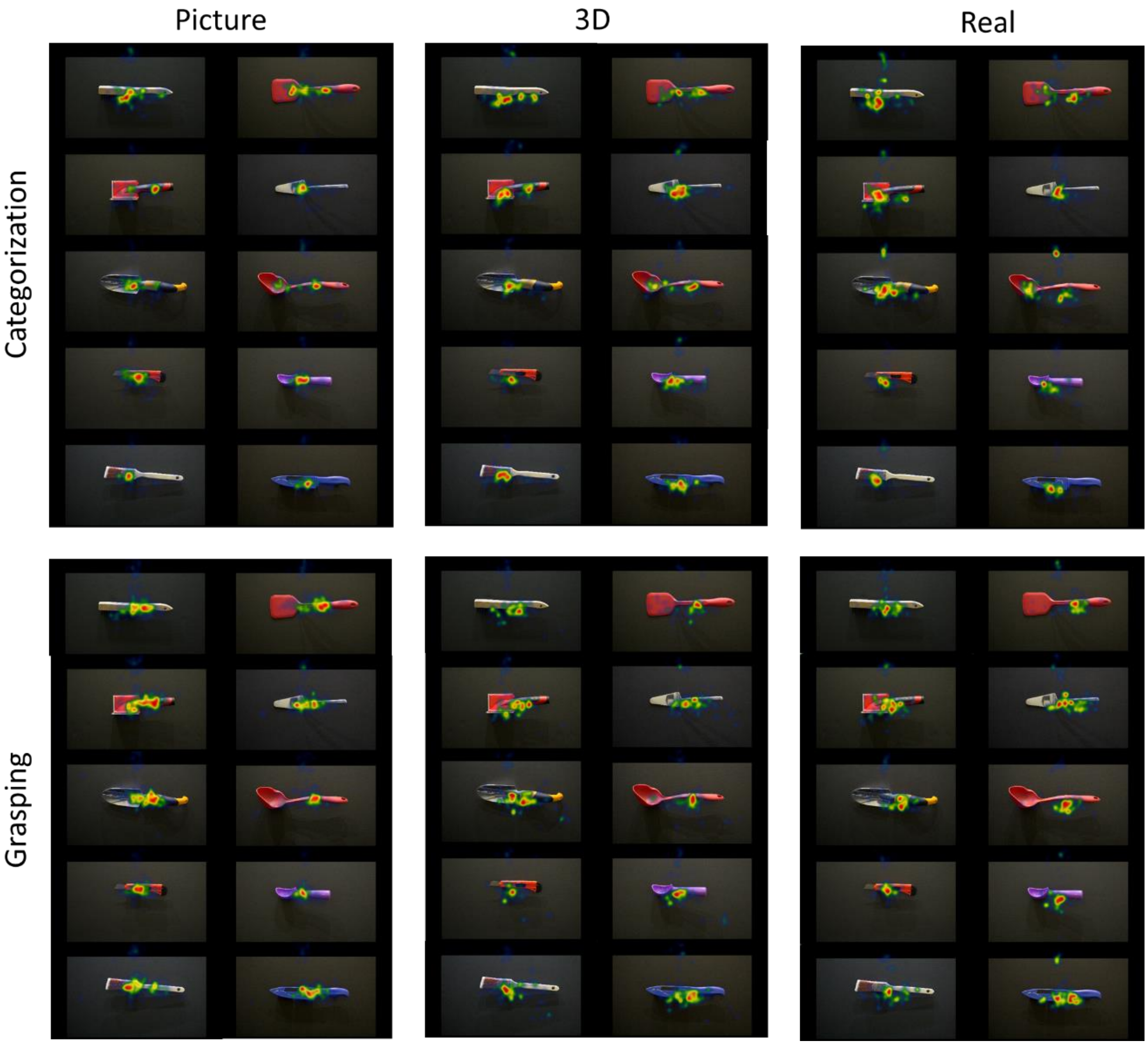


Figure 10. Heat maps generated for each Display format (from left: Picture, 3D, and Real) and for each task, the grasping task in the top row, and the categorization task in the bottom row. The warmer and denser color represent the higher number of fixation in a particular region of an object.

head end of tools, whereas in the grasping task they were located at the physical center of objects, if not closer to their handles.

The horizontal length

For this analysis, the data were then averaged across all tools to yield mean position of peak fixation as a % of tool length. The RM ANOVA for factors: ***Display Format*** and ***Response Task*** revealed that there was significant main effect of ***Task*** (F(1, 10) = 27.682, $p < 0.001$, ηp2 = 0.755). Participants were locating their gaze at 58.5% of a tool length when they were categorizing it and at 47.1% when they were grasping the tool. There was no main effect of ***Display Format*** (F<1) and the interaction between the two factors was not significant (F(2, 18) = 1.530, p = 0.243, ηp2 = 0.145). Although, the interaction term was not significant it produced a moderate effect size (ηp2 = 0.145). Therefore, the differences between in the mean position of peak fixation were further investigated for each display type were compared using a series of repeated measures t-tests. The **Figure 11** shows that the differences between the categorization task (green squares and green line for the mean) and grasping task (blue circles and blue line for the mean) was significant for real objects (t(9) = 4.863, p = 0.001) and 3D displays (t(9) = 4.863, p = 0.001) but not in case of 2D images (t(9) = 1.416, p = 0.190). The figure also show that in case of pictures the fixation were located very closed to objects COM (red square), however not in the case of real object and 3D displays. Additional series of one sample t-test were conducted to verify if the observed difference in mean fixation location for each task were significantly different from the mean COM (51%). The test revealed that in case of real objects both means for the categorization and grasping are significantly different from COM (respectively: t(9) = 2.753, p = 0.022; and t(9) = -2.493, p = 0.034). The distance was also significant for the categorization task in 3D display format (t(9) = 2.514, p = 0.033), however, it was not significant for the grasping task (t(9) = -1.512, p = 0.165). Interestingly, in case of 2D images the distance between the mean location of the most frequent gaze location was not different from COM for the categorization task (t(9) = 1.050, p = 0.321) nor for the grasping task (t(9) = -0.402, p = 0.697).

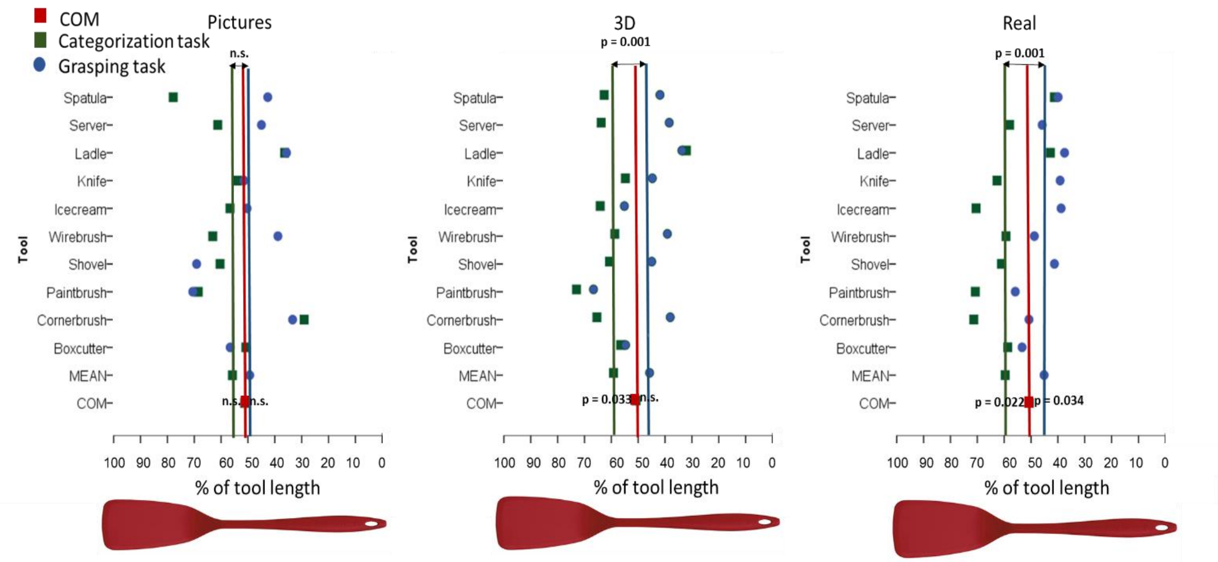


Figure 11. Locations of the most frequent fixations mapped on horizontal extent of normalized tool length. Green squares represent individual tools in the categorization task, blue circles in the grasping task, the red squares and lines represent mean center of mass (COM). The green lines represent the mean location in the categorization task and the blue line in the grasping task. Participants' fixations in the grasping task were significantly different from COM only in case of real objects (p = 0.034)

The analysis of the whole trial shows that participants performed more fixations in case of 2D images than any other display format as revealed by the main effect of ***Display Format*** in the RM ANOVA model of FC. This may be related with a fact that in the analysis of fixations by the eye-tracking software, the AOIs were drawn using the 2D images as a template, and therefore they were able to ‘capture’ more of the fixations. Participants also performed more fixations in the categorization task than the grasping task across all displays as shown on the **Figure 9a**. The analysis of the whole trial showed that participants distribute their eye movements similarly between real objects and 3D display in case of both Response Tasks whereas in case pictorial displays their eye movements are concentrated at the Center of Mass of objects. Importantly participants’ fixations in the grasping task were significantly different from COM only in case of real objects ($p = 0.034$).

Discussion

In this study gaze fixations were investigated for everyday tools displayed as 2D planar images, 3D stereo images, and real tangible objects. Based on the AOI and the whole tool types of analysis gaze patterns were compared during both the semantic classification task, and the grasping task. During object classification, gaze patterns were similar across the three display formats: the head end of the tool was fixated first and it received the greatest number of fixations during the trial. In the grasping task gaze patterns were also similar across the three Display Formats. However, in this case participants’ eye movements were biased more towards tools’ handles. The analysis of the whole tool revealed that in case 2D images eye movements where relatively close to objects’ COM in both tasks. However, in case of the 3D displays and real objects they were directed more towards the handle of objects in case of the grasping task and more towards the head of objects in the categorization task. Importantly, only for real objects the mean location of the most frequent fixation was direct significantly farther away from COM towards tools' handles. Overall, the results of this study show that the task given to the participants had a very strong influence on the pattern of eye movements, however, the display format also influence position of most frequent fixations in both tasks.

The prediction for this study were based on our previous studies using only images of tools and other objects (Skiba, Papa, & Snow, *manuscript in preparation*). We found that when asked to categorize objects to kitchen or garage or when decide if object is man-made or not our participants were fastest to explore head end of tools and they performed more fixations in that part of tools only. In case of fruits and veggies participants had a tendency to simply focusing their fixation at the physical center of objects. In this project we predicted that participants should focus their fixation at the handle of real objects in both categorization and grasping tasks. To our stimuli set up we added images in 3D in order to verify if spectroscopic cues may change the perception of 2D images. Our results showed that the task has a substantial influence on the eye movement behavior and in the categorization task there were no differences among the three display formats. However, handle of real objects received more fixations in the grasping task and handles of 3D images were also attended more than the handle of 2D images. Therefore, if the task requires to plan motor action than the parts of objects relevant for grasping receive more overt attention. Importantly, stereoscopic shape cues seem to be crucial aspect in developing a proper motor routine.

When discussing the both tasks of the current project it should be pointed out that, in the categorization task participants had to identify the category of each tool (kitchen or garage), therefore, their gaze was naturally focused on the part that allowed them to quickly identify each object, that is, the head end of tool (see also, van der Linden et al., 2015). Interestingly, the same pattern was confirmed in cases of each Display Format. Participants were faster to look on the head end of tools as measured by Entry Time to AOI (see **Figure 6**). Across the entire trial participants performed more fixation at the head end rather than handle across all display types (see **Figure 9**). Therefore, the task determined the pattern of eye movement independently of other features of stereoscopically presented images and real tangible objects. The main effect of task was also observed during the grasping task, however, here participants were deploying longer first fixation at the handle of tools independently of Display Format (see **Figure 8**).

The whole tool analysis revealed a very interesting pattern of results. Stereoscopically presented objects were explored vary similarly to their real counterparts rather than to 2D images. Much research revealed that stereoscopic cues and depth cues are fundamental for developing an effective sensorimotor plan to interact with objects in peripersonal space (Holmes & Spence, 2004). Therefore, the eye movements are sensitive to the depth cues in object that does not offer physical affordance but have features that allow to develop a proper grasp. The analysis also showed that when presented with real objects participants concentrated their fixations at the handle of tools during the grasping task.

This study seems to have a limited power to verify if physical affordance presents in real object significantly influence patterns of eye movements. The analysis of Entry Time in the grasping task reveals that the handles of real objects were access marginally faster than the head end (see **Figure 9**). Therefore, it is possible that the handles of real objects receive more attention when this part of of a tool is relevant to a context of a motor task.

The future research should expand our understating of patterns of eye movements by testing a bigger range of familiar objects. The methodology and stimulus set-up developed in this study can significantly help future researchers in testing real objects in a timely and precise fashion. It would be interesting to see if objects that are not manipulable but real differ in their exploration patterns from pictures of objects.

Concluding, this study showed that both the task and tangibility of stimuli influenced the patterns of eye movements. It seems that the handles of objects capture attention and eye movements only when an observers need to take it in consideration their motor goal and even more so when so when the object is real. This observation contrast some other studies claiming that images handles of manipulable objects automatically capture eye movements (Myachykov et al., 2013). This study also provide an evidence that picture of objects taken in color and having real size can be good proxies for real objects in perceptual tasks such as a categorization task used here.

General Discussion

Our current understanding of attention and eye movements is almost solely based on studies that used computerized images of objects. However, relying on image displays may be misleading because of the plethora of perpetual differences between the two classes of objects (see section: Real objects and their images in the General Introduction of this thesis). The goal of the present research was to verify if eye movement and covert attention were distributed differently when perceiving real objects versus their image displays. Furthermore, in one of the discussed research we aimed to verify if potential difference in allocation of eye movements between 2D images and real objects can be attributed to stereoscopic cues and therefore we tested participants on 3D display in addition to the two other display formats. Moreover, both research projects presented here used novel stimuli-presentation systems that reliably tested perception and eye movements of real object in timely fashion. Importantly, the systems are ready to be used by other researchers to cultivate our understanding of human cognition in the real world.

Object affordance and pseudoneglect

The first project used the modified version of the Posner cueing task and established that the participants were faster to detect the rapidly occurring target on the left side of real objects in the near distance from them but not when they viewed the objects from the far distance. This effect is also known as pseduoneglect and it was not present in case of the

2D images of the same objects in either near or far distance condition (respectively Study 1, and Study 2).

The discussed research provides the scientific community with a novel understanding of pseudoneglect. Although, this form of leftward bias of visuospatial attention has been commonly attributed to specialization of the right hemisphere in processing attention there is still unknown what factors produce and magnify this error in visuospatial orienting. Previous research agreed that one of the most significant factor is the distance from the stimulus in the line bisection task (Longo & Lourenco, 2006; McCourt & Garlinghouse, 2000). The magnitude of the leftward bias in the line bisection task diminishes in the far or extrapersonal space (McCourt & Garlinghouse, 2000). However, having a tool, which can interact with a stimulus in extrapersonal space can return the leftward bias (Longo & Lourenco, 2006). Notably, this study is the first one to show that the magnitude of leftward bias could be modulated by the presence of graspable objects in a reachable distance. Therefore, the pseudoneglect is not only a form of perceptual bias of attention orienting but it is related with a possibility of manual interaction with objects that is implied by objects that offer physical affordance.

Object affordance and eye movements

In the second project, the participants performed object categorization and object grasping tasks while their eye movements were measured during viewing real objects, image and stereoscopic displays. The task strongly influence patterns of eye movements. When the observers performed the categorization task their eye movements are mostly influenced by the directed towards the head end part of tools independently of display format. Interestingly, in case of the grasping task the handle received more fixations; however, this difference in allocation of fixations between heads and handles of tools was only clearly observed for real objects.

Both results are crucial for our understanding of the patterns of eye movements across different display formats. Firstly, previous research showed that eye movements are strictly linked to the task that observers have to perform (Kowler, 2011; Land, 2006; Orquin & Mueller Loose, 2013). The current project showed that if the task is perceptual such as the categorization task used in this project the display format does not have influence on patterns of eye movements. However, if participants are asked to physically interact with objects then displaying an object in a format of an image may be problematic for proper understanding of the behavior of the oculomotor system in the real world. It should be point out that real tangible objects possess parts that are appropriate for grasping and therefore attention and eye movements are directed towards those parts during motor tasks.

Limitations

The biggest limitation of the presented research is a lack of large enough sample size in particular in the second experiment. It would be necessary to verify presented conclusion of the eye movements study with a new set of objects. In case of both studies, we used novel stimuli presentation systems and further studies should be conducted using those systems to verify if they can reliably test other cognitive paradigm with new group of participants and therefore prove validity of those systems.

Future direction

The current research showed that stereoscopic depth cues are important addition to 2D images that make 3D displays perceived more like real objects in the free viewing grasping task. It would be interesting to see in the future studies if depth cues can also affect the magnitude of leftward bias of visuospatial attention when presented in reachable distance form an observer. However, it would be desirable if future studies should employ new methods that will allow pictures to look more realistic so they could imply some form of physical affordance. A possible solution in new technologies can be provided by the HoloLens project developed by Microsoft (HoloLens, 2016).

The HoloLens have ability to project a hologram on a real surface making the display both stereoscopic and putting it into the context of the real environment. Another possibility of studying the effects of stereoscopic cues would be to conduct similar research like in this thesis but using monocular and binocular viewing. Therefore, the realness and affordance of object will remain but only the stereoscopic cues would be manipulated. Controlling the 3D displays seems to be important questions because although the 3D glasses offer the depth cues those cues are in conflict with monocular cues that inform an observer that the objects does not have actual depth. Having 3D holograms presented on a real surface can provide a facilitation of such conflict because the display will be placed in the context of the real environment. Thus, using advanced 3D displays may allow researchers to discover a naturalistic form of object exploration.

Conclusion

Both projects provide us with new understating of the influence of response task, and display format on covert and overt attentional processing. The first experiment showed that graspable objects that afford action in reachable distance magnify the leftward bias of visuospatial attention. The second experiment showed that if performing perceptual task the low-level proprieties of stimuli like stereoscopic cues or tangibility do not affect patterns of eye movements. However, when the participants actually grasped an object then the handles of real object receive more fixation and in result our attention.

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