Locating objects in virtual reality – the effect of visual properties on target acquisition in unrestrained reaching

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ABSTRACT

Locating objects in virtual space is not the same as locating them in physical space. The visual properties of the virtual object can affect the perception of its spatial location, and hence the ability to accurately co-locate the hand and the object. This paper presents an investigation into the effects of object geometry and proximity brightness cues on the time-to-target of a virtual reality reaching and grasping task. Time-to-target was significantly affected by object geometry, but not by brightness cues. We conclude that object geometry needs to be carefully considered for applications where accurate co-location of hand and object are important.

1. INTRODUCTION

With rapid advances in technology and diminishing costs, Virtual Reality (VR) is emerging as a rehabilitation tool which is able to engage patients and improve treatment compliance and outcomes (Bryanton et al, 2006; Rizzo and Kim, 2005; Thornton et al, 2005). There is evidence that it can provide distraction from pain (Hoffman et al, 2004, 2000, 2003, 2001) and aid neurological and physical rehabilitation (Jack et al, 2001; Kizony et al, 2003a; Merians et al, 2002; Piron et al, 2001; Sveistrup et al, 2003).

Virtual Reality can provide a rich visual context with meaningful ecologically valid activities which support the higher functional tasks that promote motor learning. Furthermore, VR offers the ability to present elements within the virtual environment (VE) whose visual perception and interactive properties can be manipulated to have precisely determined characteristics, or even discrepancies, in order to subtly influence participant behaviour and perception (Murray et al, 2006; V. Powell et al, 2010; W. Powell et al, 2006, 2007, 2013).

However, whilst it is recognised that movement and perception in a virtual environment is not directly equivalent t to the real world, there is little work to date investigating the ways in which upper limb movement is impacted by the design of the VE, and thus a lack of information to support designers to create optimised VR applications which support the rehabilitation goals whilst minimising fatigue or frustration caused by visuo-motor mismatches during task performance.

2. REACHING AND GRASPING IN VIRTUAL REALITY

Visual compression of distances in VR is a well documented issue (Armbruster et al. 2008; Frenz et al, 2007) and this can influence the user's ability to accurately locate and reach an object in virtual space. Whilst some evidence suggests that practice and training can afford some adaption to this distance compression (Jones et al, 2009), nevertheless it is a potential source of frustration and difficulty, which may add to the physical and cognitive load when using VR for physical rehabilitation. Thus, to facilitate the creation of ecologically valid and task-relevant virtual rehabilitation environments, it is important to understand the ways in which the visual properties of an object may affect the ability to locate it in virtual space, and how this can be used to optimise the design of upper limb reaching and rehabilitation tasks.

From a clinical practitioner's perspective, the ability to motivate patients to reach with their arms and hands, and intercept to a predetermined point in space has notable rehabilitation value. In order to achieve this, a number of studies have used spheres as target objects in reaching tasks in the evaluation of the potential for VR in a rehabilitation context (Armbruster et al, 2005, 2008; Kizony et al, 2003b; Loomis and Knapp, 2003; Viau et al, 2004). Spheres have a natural implied narrative context for goal orientated tasks as they readily encompass

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balls to hit or catch in sporting simulated games, or bubbles or balloons to pop, and this can be important for engagement with physical rehabilitation and immersion in VR (Craig, et al, 2009). An alternative approach that some VR applications often find appealing is to render 3D objects as realistically as possible to enable the knowledge of the object itself in the real world to convey a sense of perspective and distance (Goldstein, 2002), and to enhance the immersion or sense of presence (Kauffman et al, 2008; Subramanian et al, 2007). It remains unclear however what impact these approaches have on the user's perception of target location and distance to interception, and hence their reaching performance. Indeed, abnormal reaching behaviour has been noted during object acquisition tasks in VR, but the underlying factors causing this aberrant movement are not well understood. Where movement differences are noted in VEs compared to normal environments, the possible explanations given often include issues with spatial perception of the target object (Knaut, et al, 2009; Magdalon, et al, 2008, 2011; Viau, et al, 2004). In addition some of the studies indicate behaviours that are likely to implicate properties of the target object itself and even demonstrate differences in behaviour between objects with different characteristics (Magdalon, et al, 2008, 2011). This latter point is compelling as it suggests that the visual representation and properties of target objects within the VE and the visual cues they convey to the user might be responsible for altering motion patterns. This has significant implications for rehabilitation or neuropsychological tasks in VR that involve reach to grasp actions, and suggests the need to establish its potential effects and how to ameliorate them. It also raises the question of whether object properties could be optimized to given tasks and, furthermore, whether their properties could be manipulated to influence motion behaviours to further enhance rehabilitation.

In the majority of studies published to date the type of virtual target objects used for reaching tasks varies widely, and there has been little work exploring the effect of the visual characteristics of these different objects on target acquisition time or reaching behaviour. Previous studies have indicated that whilst users can locate the general position of a virtual object in peri-personal space (Armbruster et al, 2008), they may have issue with spatial perception within a VE. This may become more pronounced during the final corrective motions to hand trajectory when ascertaining the precise location of the object in the terminal or deceleration phase for reaching and grasping (Hu et al, 2002; Kuhlen et al, 1998; Madison et al, 2001; Magdalon et al, 2011; V. Powell et al, 2010).

If altering the visual properties of an object can improve the ability to locate the object in virtual space then this may improve task performance and improve the rehabilitation outcomes. In addition this may improve participant confidence, immersion and engagement with the given tasks and avoid undesirable and atypical reaching strategies (V. Powell, 2013). Therefore it is important to establish which visual properties affect the time taken to locate the object in virtual space in order to inform better design of a virtual environment (VE) for upper limb rehabilitation. It would seem reasonable to start by evaluating the more commonly used target objects alongside objects with alternative geometries.

It has previously been demonstrated that the visual properties of target objects could influence the ability to accurately reach the object in virtual space (V. Powell et al, 2010), but the relatively small sample size (n=13) and large number of experimental conditions (n=8) limited the conclusions which could be drawn from statistical analysis of the data. Nevertheless, it was clear from this preliminary work that manipulating the visual properties of a target object could impact the time to target in reaching tasks, potentially reducing the biomechanical load imposed by "loitering and fishing" for targets with ambiguous depth cues.

The study presented in this paper builds upon insights gained from this earlier work, presenting users with a virtual apple-picking task using three different objects as reaching targets (Figure 1):

1. An apple - to provide an ecologically valid realistic model with visual narrative to the orchard scenario and with object familiarity and relatable scale.
2. A sphere - the most commonly used simple object in published upper limb VR scenarios (usually representing balls or bubbles).
3. A 20 sided polygon (icosahedron) - a low polygon model with inherent visual depth cues due to intra object landmarks for surface motion parallax, and occlusion or dissocclusion of surface and edge geometry during relative movement.

It is reasoned that a reduction in "loitering" or time to target, in the deceleration phase of reaching, may indicate a confidence in the user's perception of the spatial location of the virtual target objects, improving movement efficiency and thus better supporting rehabilitation goals. This study thus sets out to determine the relative impact on loiter time of the visual cues inherent in different target object geometries, and furthermore whether increasing brightness cues on proximity will enhance or detract from this.

Figure 1. *The three object shapes used in the study.*

3. METHOD

The experiment was a repeated-measures within-subjects 2 x 3 factorial design (shape x brightness), with the objects either staying constant, or increasing brightness on proximity, for each experimental condition. The independent variables were object shape / parallax cues and brightness change (Table 1). Time in milliseconds from object proximity to object acquisition (loiter time) was the dependent variable.

Table 1. *The experimental conditions for the reaching study.*

	Apple	**Sphere**	**Polyhedron**
Shape only (no brightness change)	Condition A	Condition B	Condition C
Increase brightness on proximity	Condition D	Condition E	Condition F

A power calculation conducted on the basis of the data from the previous experiment (V. Powell et al, 2010), and twenty nine healthy volunteers (17 male, 12 female, age 19-46) participated in this experiment. The tasks were carried out in a Virtual Reality laboratory with a 'Virtual Orchard', created in 3D Studio Max and rendered into an interactive format using Open Scene Graph (Figure 2).

Figure 2. *The virtual orchard used in the study.*

Participants were equipped with Ascension Technology (Flock of Birds) magnetic motion trackers attached to the antero-lateral margin of the acromion process of the scapula, and on Lister's tubercle of the wrist on the dominant hand, and their movements were tracked in the Virtual World with a virtual representation of the same hand.

The target objects were asymmetric apples (1500 polygons), spheres (960 polygons) or icosahedrons (20 polygons), all were 10cm in diameter (Figure 1).

Ten objects were presented for each condition. The target object positions were varied on the horizontal and vertical axis and in depth from the screen, and the same configuration was maintained for each condition.

It has been noted that colour has a differential effect on depth perception, with a general trend to overestimate distances to red targets and underestimate distances to green targets (Gentilucci, et al, 2001). No distinct colour has been identified with veridical distance estimation. Therefore to minimise the confounding effect of colour, each variant of the object was rendered in both red and green with non-uniform surface material textures to ensure that any observable differences in motion were due to the object shape.

Virtual baskets provided both a narrative context and a means of completing the interactive task with alternating movement patterns at the shoulder to prevent excessive repetition. They were initially displayed on screen, and once their role had been explained to the participant they were displaced to their position on the participants back. The participants dropped each ‘apple’ into the virtual basket after successful object acquisition.

The virtual camera was set to match the starting position of the participant, with a field of view of 100^o and a starting height of 1.6m above the ground plane. The stereoscopic scene was projected onto a 4.5m x 2m display screen using a pair of Christie 7700 Lumen projectors with polarising filters. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself. An eye-hand vector camera tracking algorithm described previously (V. Powell and Powell, 2010) was used to orient the virtual camera. The target objects were projected stereoscopically in negative parallax (i.e. to appear as if they are in the room).

If the inherent visual cues of the target object are to influence the perception of the final spatial determination of that object, it would be reasonable to expect this to be most evident in the deceleration phase of reaching and grasping actions. Therefore based on the observations of Kuhlen, et al, (1998) the “loiter time” is taken from hand proximity to the object (30cm), to object acquisition. This “loiter time” or time to target is the primary dependent variable used in this study. The “loiter time zone” initiated recording as soon as the reaching hand passed within it (and paused if the hand left the zone) recording the cumulative duration it took for the hand to pass through the zone and successfully contact the target object.

3.1 Procedure

Participants were introduced to the physical environment of the VR suite and guided through the dynamics of the task. The magnetic sensors were then attached to the wrist and shoulder and trailing wires secured. Participants were asked to repeat the shoulder range of motion actions to ensure they were free to do so unhindered.

At the start of each experimental trial the participants had a non-interactive view of the “Orchard” with the baskets in view. The starting position of the sensors was recorded and used to initialise the camera view in the virtual scene, which was dynamically linked to the actions of the participant. The hand movement of the participant was mapped to a virtual representation of the dominant hand.

A demonstration object (of the same type and visual behaviour as the test condition) was presented at eye height 2m in front of the participant. Data recording was initiated after the demo object had been successfully acquired and dropped into the virtual basket.

For each condition, the ten test objects (5 green and 5 red) were displayed one at a time (alternating colours) in preset locations within the participant’s field of view. To avoid pre-planning the next move, each object had to be acquired and dropped successfully before the next object was revealed. The time from object proximity (30cm from the object centre) to object acquisition was recorded for each test object.

For conditions A-C the object brightness remained unchanged throughout the trial. For conditions D-F, the brightness automatically increased once the hand reached the loiter zone.

4. RESULTS

A mean value was calculated for the time-to-target for the 10 objects in each experimental trial, using the time in ms from object proximity (30cm from the centre of the object) to object acquisition (Table 2) . In order to accurately reflect the wide variations in performance in a normal human population no data filtering was used in this study.

Table 2. *The time-to-target in ms for each experimental condition (StDev in brackets).*

	Apple	**Sphere**	**Icosahedron**
Shape only (no brightness change)	3106*(1966)*	3883*(3388)*	3006*(1700)*
Increase brightness on proximity	2957*(1748)*	4140*(4059)*	3127(*1893)*

A repeated measures 2-way ANOVA (shape x brightness) demonstrated a significant effect of shape on time-to-target ($F_{(2,56)}=3.62$, $p<0.05$), but no significant effect of brightness on time-to-target ($F_{(1,28)}=0.09$, $p=0.77$).

Mean times-to-target durations were compared for the brightness changing conditions and the constant brightness conditions. There was no significant effect of brightness on time-to-target ($F_{(1,28)}=0.09$, $p=0.77$).

Post-Hoc testing revealed that time-to-target was significantly longer in the sphere condition compared to the icosahedron condition ($p<0.05$) and also longer compared to the apple condition, although this did not reach 5% significance level ($p=0.07$). There was no significant difference between the icosahedron and apple conditions (Figure 3).

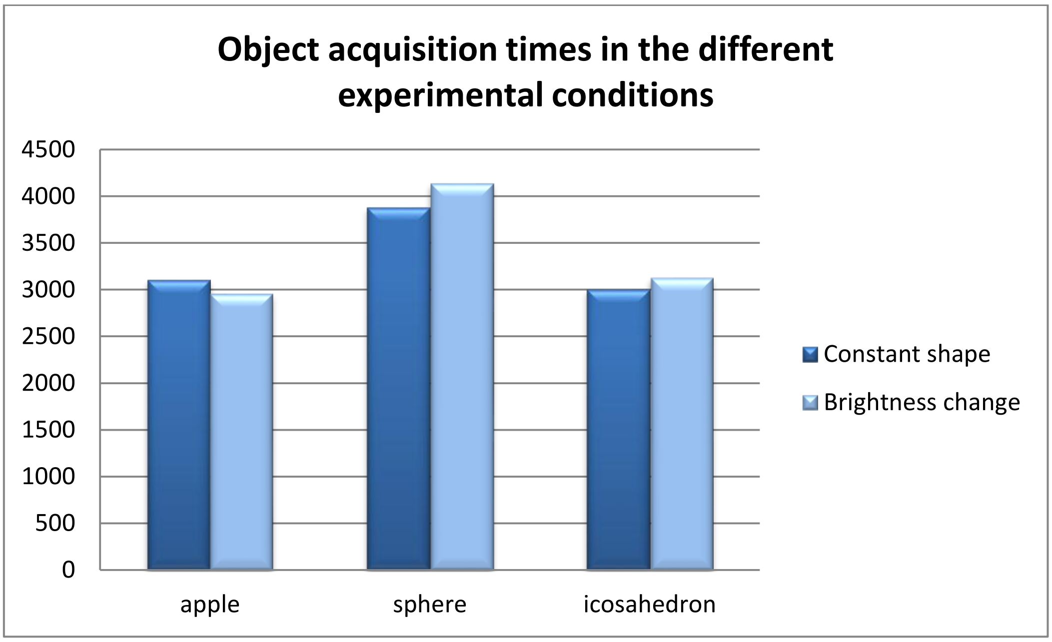

Figure 3. *Mean Time-to-target (ms) for each of the 6 experimental conditions.*

5. DISCUSSION

The results from this study confirm that the geometry of a target object significantly affects the time spent in the terminal phases of object acquisition. The sphere, although a commonly used object in VR upper limb tasks, demonstrated the longest loiter times overall, and the difference between it and both the apple and the icosahedron was statistically significant. Interestingly there was no statistically significant difference between the apple and the icosahedron, suggesting that the unconventional simple geometric target object with little real world familiarity or sense of inherent scale as an interactive object, performed as well as the modeled target object based on a real world object that many individuals should be familiar with.

There was no significant effect of the brightness changing condition on time to target, suggesting that the absolute depth cues provided by object geometry, in peripersonal space, was a more important design consideration.

This study supports the findings of the previous smaller study regarding the poor performance with spheres as target objects (V. Powell et al, 2010), and confirms that the common practice of the use of spheres as target objects in VR tasks that involve reaching and grasping is potentially a confound for research outcomes and possibly deleterious for rehabilitation goals. The sphere geometry has been demonstrated to require a longer duration for the deceleration phase of reaching.

No significant difference was found between icosahedrons and the modeled apples as target objects. This suggests that for simple Virtual Environments, that do not have an imperative need to attempt photorealism, low polygon models can be found that will provide sufficient depth cues for determining spatial location in reaching and grasping tasks without the need for more detailed modeling. The simpler geometric object, at 20 polygons, requires less than 2% of the computational load of the apple object, which could have significant implications for software performance, particularly in applications with multiple target objects. The similarity between the performance of the low-poly icosahedron and the apple may be due to the fact that both objects have visual variation at different angles and distances, providing richer depth cues than the symmetrical spheres. There might also be a trade off with the apple providing natural depth cues through familiarity and scale, whilst the icosahedron which effectively lacks a relative scale or familiarity in the context of its environment does however provide richer depth cues through its intra object landmarks that provide surface motion parallax, along with the occlusion or dissocclusion of its surface and edge geometry during relative movement. The spheres however, do not typically provide any of these spatial cues (Figure 4).

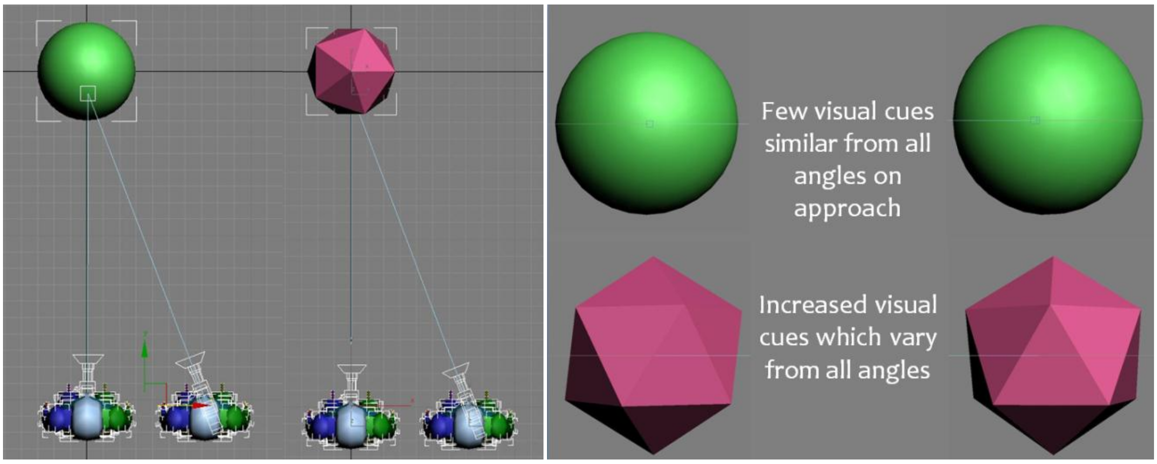

Figure 4. *Varying viewing position (left) provides additional visual cues to support accurate depth perception with the icosahedron, but not with the sphere (right).*

The manipulation of target object geometry had a more significant effect on time to target than altering brightness, however it should be noted that the transitional brightness change did not attempt realism but rather operated as a proximity cue as seen in a number of computer games. In this regard it would appear to be ineffective in a VR setting and perhaps further investigation of more realistic brightness changes in response to global illumination or local intense light sources might be worth further investigation, as might the reflective nature of the target objects surface material.

Although shadows and interreflections have previously been found to be significant cues when determining the accurate perception of distance between two object surfaces (Hu, et al, 2002), these are rarely rendered in VR action tasks for physical rehabilitation, and are computationally demanding to deliver with real time interaction in any extensive virtual environment. Until VR achieves near veridical portrayal of objects, even with the addition of shadows and interreflections, depth cues may need augmentation. Further investigation of object properties to facilitate absolute spatial location and subsequent movement behaviours is being undertaken.

It should be borne in mind that these results are from a population of healthy individuals, and further investigation is proposed in order to establish the effect of target object geometry among a population with shoulder restriction and pain. Nevertheless, it is relatively simple to manipulate object geometry to facilitate reaching to grasp rehabilitation tasks or to support more generic upper limb exercise outcomes, and it is certainly worthy of consideration during application design. Selecting object geometries which support accurate spatial location may help to reduce frustration and fatigue in VR upper limb tasks.

This study aims to facilitate informed design and highlight an often overlooked component of VR. Where practical, virtual rehabilitation application design should have some consideration of target object type in relation to the desired application goals. A summary of functional task requirements and their respective suggested preferences for potential target object visual properties is offered for consideration (Table 3).

6. CONCLUSION

This study confirms that object shape has a significant effect on the time taken to locate and grasp a virtual object in 3D space, and that spherical balls and bubbles often used in upper limb rehabilitation games may not be the most suitable object shapes, prolonging the time taken to locate the object in space, and consequently increasing the risk of fatigue or disengagement during task performance.

Although there is much work still to be done before fully optimised virtual tasks can be designed, it is clear that it is possible to improve task performance without increasing computational load on the VR system by implementing some simple changes in the design of the target objects.

Table 3. *Suggested object characteristic preferences for action tasks.*

Functional Task requirements	*Preferred Target Object Characteristics*	*Least desirable Target Object Characteristics*
Pointing to target, Interception of target, Touching target. Where active and engaging movement needs to be encouraged and precise motion is not critical to outcomes	Any, Spheres are simple to model and provide a narrative context for the user to relate to and engage with the task. Non uniform surfaces are preferable particularly for moving objects	Abstract objects with little or no narrative engagement or those with high computational demand.
Grasping or surface contact tasks with precision in a close constrained space where objects are in close proximity.	Objects with rich visual spatial cues e.g. either icosahedrons or realistic modeled objects with functional familiarity, textures, interreflections and shadows.	Spheres and objects that present the same visual information throughout different viewing angles.
Reaching and Grasping targets at varying distances, without constraints on participant movement, relating to tasks with specific ecologically valid real world outcomes.	Objects with contextual familiarity and relevancy e.g. Realistically modeled representations of real world objects.	Spheres, abstract icosahedrons and objects with high computational demands for visual proximity cues.
Reaching and Grasping targets at varying distances, without constraints on participant movement, relating to tasks with specific functional movement outcomes or accuracy in spatial perception	Objects with rich visual spatial cues and low computational demands e.g. Icosahedrons	Spheres or shapes that provide minimal motion parallax cues on approach or realistically detailed models with high computational demands.

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