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Design and Evaluation of Visual Interpenetration Cues in Virtual Grasping

Mores Prachyabrued and Christoph W. Borst

Abstract—We present design and impact studies of visual feedback for virtual grasping. The studies suggest new or updated guidelines for feedback. Recent grasping techniques incorporate visual cues to help resolve undesirable visual or performance artifacts encountered after real fingers enter a virtual object. Prior guidelines about such visuals are based largely on other interaction types and provide inconsistent and potentially-misleading information when applied to grasping. We address this with a two-stage study. In the first stage, users adjusted parameters of various feedback types, including some novel aspects, to identify promising settings and to give insight into preferences regarding the parameters. In the next stage, the tuned feedback techniques were evaluated in terms of objective performance (finger penetration, release time, and precision) and subjective rankings (visual quality, perceived behavior impact, and overall preference). Additionally, subjects commented on the techniques while reviewing them in a final session. Performancewise, the most promising techniques directly reveal penetrating hand configuration in some way. Subjectively, subjects appreciated visual cues about interpenetration or grasp force, and color changes are most promising. The results enable selection of the best cues based on understanding the relevant tradeoffs and reasonable parameter values. The results also provide a needed basis for more focused studies of specific visual cues and for choosing conditions in comparisons to other feedback modes, such as haptic, audio, or multimodal. Considering results, we propose that 3D interaction guidelines must be updated to capture the importance of interpenetration cues, possible performance benefits of direct representations, and tradeoffs involved in cue selection.

Index Terms—Virtual grasping, virtual reality, visual feedback

1 Introduction

We investigate visual feedback for virtual grasping. Grasping quality is important in VR applications such as training for manual assembly [1] or design review of vehicle control layouts [2]. There is also a growing interest in hand interaction for recent technologies: e.g., see [3], [4], [5], [6] for related work using Kinect, Leap Motion, Digits, and interactive surfaces, respectively.

Hand-object interpenetration, where a real hand sinks into virtual objects due to the lack of real physical constraints, is a fundamental problem for hand-based interaction. Past visual interpenetration studies, which usually did not consider grasping, are inconsistent and provide potentially-misleading guidelines if applied to grasping (Section 2). The relative effectiveness of different visual cues for grasping systems is also not known. We address this with a new study of visual feedback for grasping.

Interpenetration contributes to artifacts such as a "sticking object" when exaggerated finger motions are required for release, degrading release performance and subjective experience [7] and contributing to fatigue [8]. Users may reduce such problems using "light touch" [9], [10]. Visual cues may help a user understand and control this light touch, as suggested by a prior study of two minimal (baseline) approaches [10]. Specifically, allowing visual interpenetration (Fig. 1, inner hand, IH) produces lighter touch than a visually-constrained virtual hand (outer hand, OH), but users dislike IH. We seek to mitigate the tradeoff or provide better results than baselines.

Other approaches to deal with penetration include haptics [2], [11] or audio [11] to improve hand behavior, and a special release mechanism [7] to reduce aftereffects. Even with such techniques, it is important to understand the impact of different visual approaches that may be used in combination with them, and to identify the best visual approaches for fair comparison to non-visual approaches. Visual rendering is almost always present with VR grasping. Successful use of visuals or haptics leaves the audio channel free for other purposes.

We do not study haptic feedback here and we do not expect it to eliminate penetration in the near future. Whole-hand force devices are promising in some applications, but they have limits in degrees of freedom, stiffness, and earth-referenced forces without devices that are complex, costly, and restricting [12]. This may lead to more development of minimal or passive haptic approaches that can aid users but cannot constrain motion physically, e.g., [1], [2]. Visual feedback may be preferred to some such approaches [1]. Additionally, recent hand sensing work increasingly points to optical hand tracking with minimal or no worn devices.

- *M. Prachyabrued is with the Faculty of Information and Communication Technology, Mahidol University, Thailand. E-mail: mores_p@hotmail.com.*
- *C. W. Borst is with the Center for Advanced Computer Studies, University of Louisiana at Lafayette, LA 70503. E-mail: cwborst@gmail.com.*

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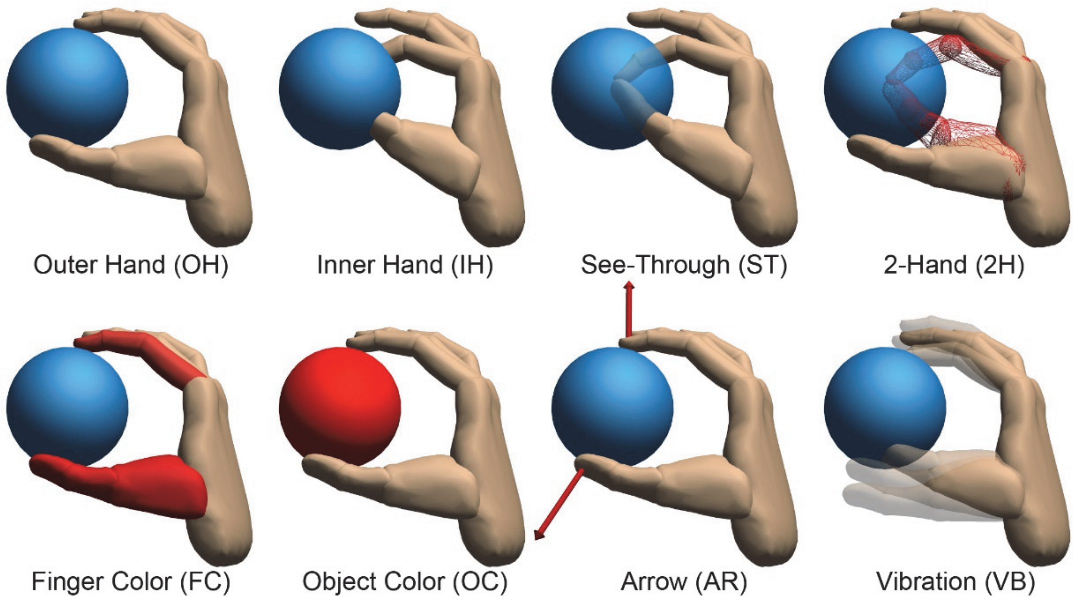

Fig. 1. Visual cues investigated in our studies, considering those common in grasping systems and also including novel aspects (ST, 2H, VB).

Regarding the approach of a heuristically-triggered release mechanism [7], visual cues to improve behavior remain important. Some grasp methods cannot readily incorporate the mechanism, e.g., [3], and most do not. Heuristics do not always trigger consistently. Release motions influenced by mechanisms besides the real hand may have side effects proportionally to penetration depth [7], [13]. Light touch can also improve simulation stability and reduce visual-proprioceptive discrepancy for constrained visuals such as OH extensions.

We conducted experiments to understand various approaches to visual feedback, considering those common in grasping systems, and also including novel aspects. A design study tuned design choices for each visual technique, and a main study evaluated performance (penetration and release) and subjective rankings. Two minimal techniques (IH and OH) provided baselines for comparisons. Section 3.2 motivates the other techniques.

The top-level contributions of this paper are:

- Design and evaluation of visual cues to help users control grasping. Prior work on grasping cues is ad hoc, with little or no study guiding choices, and guidelines are inconsistent.
- Novel aspects in the cues: See-through (ST), vibration (VB), and a modified ghost hand (two-hand, 2H).
- Main result: The best-performing techniques reveal a penetrating hand directly. 2H gives good performance and reasonable subjective experience. Color techniques (OC and FC) may be preferred for best subjective experience with some performance compromise.
- Update to a common 3d interaction guideline about visual interpenetration.

Our main results were initially presented in [14]. We now present the complete design study, an additional session (technique explanation), added correlation analysis, and a suggested interaction guideline.

2 Related Work

Studies by Lindeman et al. [15] and Burns et al. [16] support the use of a constrained virtual hand rather than a penetrating hand, but the studies did not consider grasping. Such results support a standard 3D interaction guideline of avoiding penetrating visuals [17]. Several grasping systems included mechanisms to visually constrain a hand, e.g., [9], [18], [19], [20], [21].

In contrast, Prachyabrued and Borst [10] showed how a constrained hand reduces performance and causes users to misunderstand grasp. Durlach et al. [22] previously showed similar results for a pointing task. Our findings in the following sections extend this to show that the penetrating and constrained hand baselines rank among the best and worst of several techniques in terms of performance. Furthermore, we show how some techniques mitigate the tradeoffs between these baselines.

Lindeman et al. also considered changing finger color to communicate interpenetration depth to improve users' understanding [15]. Color changes have been included in various grasping systems, e.g., [1], [2], [18], [23], [24]. Ullmann and Sauer [23] suggest that a ghost hand technique would be helpful in combination with discrete color effects. They changed phalanx color to indicate contact and changed whole hand color to indicate a valid grasp. The ghost technique represented real hand state as a wireframe rendering while also showing a constrained solid hand. Gomes de Sá and Zachmann [1] used discrete object color changes and a ghost technique for grasped objects, and they also considered vibrotactile cues. Their results suggest the object color effects are preferred over vibrotactile collision cues. Moehring and Froehlich [2] showed that discrete phalanx color changes, indicating phalanges defining a grasp, can improve subjective ratings. Achibet et al. [24] compared discrete and continuous color changes on a virtual mitten. Continuous change provided lighter grasp, better grasp force discrimination, and appeared slightly preferred over discrete change.

Rusak et al. [25] made an object transparent to show contact region, through an object, for a constrained hand. This improved finger positioning on a block. Unlike this work, we present a transparency cue (ST) that reveals a penetrating hand, and the object remains opaque with respect to other objects besides the hand.

Fabiani et al. [11] studied visual and auditory cues as a substitute for, and in combination with, force feedback. The visual cues consisted of LED-type force level indicators. The grasped object was deformable, avoiding the interpenetration problem. The study asked subjects to compress the object while moving to a target. The main result was that all feedback types reduced the amount by which the object was squeezed, and force feedback provided a more balanced squeezing across fingers. In contrast, we consider the interpenetration problem, we study several more direct visual feedback types, we use a pick-and-drop task without specific instructions about hand closure, and we include subjective results.

Hand visual fidelity has been studied, e.g., [22], [26], [27]. A moderately-realistic 3D hand model has been seen to provide better targeting than abstract models [27] or very crude models [22]. In our study, we focus on visual cues added to a similarly-realistic 3D hand model, and we focus on grasping.

Visual cues for inter-object contact have also been studied outside of grasping. The most relevant work, by Sreng et al. [28], designed proximity and contact cues for assembly or maintenance simulation. They included a lighting effect illuminating contact areas and visual glyphs (arrow, disk, and sphere) conveying proximity, contact location, and contact force. Glyph properties, such as size, color, or deformation could be functions of proximity or force. Evaluation showed that subjects preferred color-coded glyphs for proximity, deformation for force, and lighting to mark contact area. In our work, we include per-finger arrow glyphs (AR) that scale with contact to show force or penetration. They resemble the force arrow glyphs for grasping of Borst and Indugula [9].

Several grasp techniques could be impacted by our findings because they share the finger penetration and release problem, e.g., [2], [3], [9], [29], [30]. A more detailed summary can be found in [7]. As already noted, some of these techniques include visual contact cues, but their relative effectiveness is not known.

3 Methods: Grasping and Visual Cues

3.1 Grasping Implementation

We implemented grasping using a virtual spring coupling between virtual and real (tracked) hands. The approach is known from previous work on physically-based grasping [9], [10]. The virtual hand model, also called the spring hand, is moved by a physics engine as a result of spring forces in the coupling. It is also affected by the physics engine's collision and response mechanisms, such that the spring hand remains outside object boundaries. The coupling contains one linear spring to pull the virtual palm towards the real palm, one torsional palm spring for palm rotation, and 20 torsional springs for finger joints. These joints follow a common model [31] with 3 joints per finger: a 2-dof metacarpophalangeal joint (MPJ) for first knuckle abduction and flexion, a 1-dof proximal interphalangeal joint (PIJ) for second knuckle flexion, and a distal interphalangeal joint (DIJ) for third knuckle flexion. The thumb has a 2-dof trapeziometacarpal joint (TMJ) in the palm for roll and abduction, a 1-dof MPJ for first knuckle flexion, and a 1-dof IJ for second knuckle flexion.

The visual hand geometry is derived from a Viewpoint Datalabs model with 16 rigid segments. The physics engine is the NVIDIA PhysX SDK. Each of the 20 finger springs is implemented using a PhysX revolute joint. The palm springs are implemented using equations from [9]. The thumb springs are 2.1 times stiffer than other digit springs, as suggested by prior work on optimizing relative spring stiffness [32]. A PhysX parameter is set to allow collision shapes to overlap by 0.6 cm for improved contact simulation. Correspondingly, hand collision shape is larger than visual shape.

3.2 Visual Feedback Techniques

Here, we introduce the feedback types, including their adjustable parameters for the first study stage. Fig. 1 provides an overview.

3.2.1 Inner Hand (IH)

Inner Hand is a baseline technique that presents an articulated 3D hand model following the user's real (tracked) hand. It produces unpleasant visual interpenetration, but it is known to produce lighter touch for better release performance when compared to Outer Hand [10].

3.2.2 Outer Hand (OH)

Outer Hand is a baseline technique presenting a 3D hand model constrained to avoid visual interpenetration. We implement it by showing the simulation-controlled spring hand configuration (Section 3.1). Users subjectively report OH as more natural than IH in [10].

3.2.3 See-Through (ST)

See-Through shows an inner hand model but reveals the penetrating portion, motivated by the potential to have the better performance of IH while making the visual interpenetration less disturbing. To our knowledge, this is a novel rendering style for grasping (Section 2). It somewhat resembles augmented reality (AR) systems where real hand parts are seen, e.g., [3], so results may give some insight into acceptability of this AR feature.

ST makes front-facing surfaces of grasped objects appear semitransparent at pixels that would otherwise occlude the inner hand. ST transparency level is tuned in our design study. Its OpenGL implementation is:

1. Clear stencil buffer values.
2. Render object's back faces to depth buffer.
3. Render hand while setting stencil values of hand pixels (passing depth buffer test).
4. Render object's front faces semitransparently, using stencil buffer to draw only to pixels from (3).

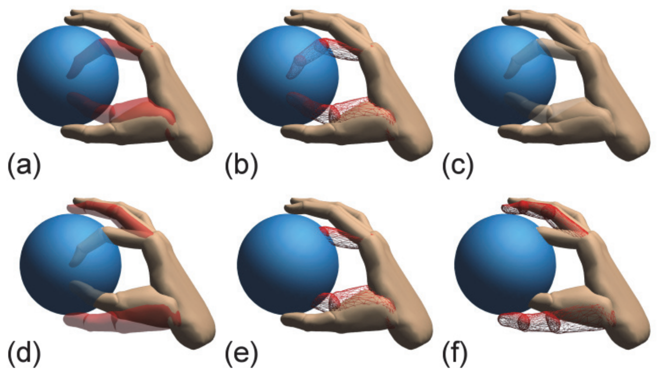

Fig. 2. Some of the 2H ghost variations: (a) colored-semitransparent inner see-through, (b) wireframe, (c) skin-semitransparent, (d) outer position, (e) occluded, (f) outer wireframe, occluded.

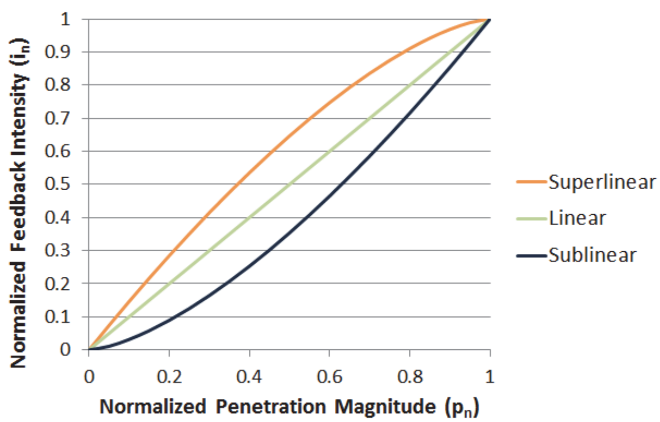

Fig. 3. Mapping functions. Values are normalized such that 1 represents maximum value for interpolation range and feedback effect magnitude. Sublinear is $i_n = p_n^{1.5}$ and superlinear is $i_n = 1\text{-}(1\text{-}\ p_n)^{1.5}$.

5. Render object's front faces solidly, using stencil buffer to avoid drawing over pixels from (3).

3.2.4 2-Hand (2H)

2-Hand resembles ghost hand techniques and shows both inner and outer hand models. 2H attempts to combine the natural impression of OH with additional understanding about real hand state provided by IH, which may improve hand control. Both ST and 2H can be considered ways to directly reveal inner hand state.

We consider 12 presentation styles for 2H (Fig. 2). Users can adjust three parameters called ghost position, rendering type, and inner hand visibility. Ghost position selects which of the two hands is drawn differently than normal, thereby specifying whether the inner or outer hand is considered the ghost (Fig. 2a vs. 2d). Rendering types for the ghost hand are colored-semitransparent (Fig. 2a), wireframe (Fig. 2b), and skin-semitransparent (Fig. 2c). The visibility options are see-through or occluded, referring to the appearance of the inner hand with respect to the grasped object (Fig. 2b vs. 2e).

Prior 2H work mainly uses an occluded inner ghost with wireframe or colored-semitransparent rendering. We added the see-through option to combine ghost techniques with ST. Transparency level is adjustable, but we re-use ST level for consistency.

3.2.5 Finger Color (FC)

Finger Color presents an outer hand model with fingers colored based on grasp. As closure increases, finger color changes continuously from normal to red. Unlike the above techniques, FC and the remaining techniques represent finger closure indirectly.

We use red because we expect it has strong visual impact, suggests "stop", and because it is common in prior work, e.g., [1], [9], [15], [28]. We consider different rates and mapping (interpolation) types for changing color from normal to red, and we also consider penetration vs. force representation. Mapping types are linear, superlinear, and sublinear, specified in Fig. 3. Nonlinear mapping may be useful to increase impact in a certain part of motion range or to counteract perceptual nonlinearities in color change. Penetration, p, is computed per digit as the distance between its tips in outer and inner hand configurations. Normalized penetration, p_n, is $min(p/R, 1)$, where R = 5.25 cm, the radius of a ball in a study. The mapping function converts this to normalized feedback intensity, i_n. Rate is set by a scale factor, s_f. Per penetrating finger, we then compute an RGB vector for color, fc, as:

$$fc = SC + (RC - SC) \cdot s_f \cdot i_n \,, \qquad (1)$$

where SC is normal color and RC is red (RGB vectors). Color channels are clamped so change does not exceed the RC target.

We also consider two closure representations: penetration and force. Penetration representation is as described above. For force, a feature of virtual springs is incorporated so color better represents forces exerted on the object. Due to the thumb spring scaling (Section 3.1), the thumb penetrates less than a finger when exerting equal force (however, when multiple fingers are used, the thumb exerts more force than one finger). The force representation multiplies normalized feedback intensities for thumb and other digits by $m{\cdot}s$ and s, respectively, where m is thumb stiffness scale (here, 2.1) and s is $2/(m+1)$. This shifts some color to the thumb while maintaining an intensity sum, making color distribution match force.

3.2.6 Object Color (OC)

Object Color presents an outer hand and varies the grasped object's color. The color changes continuously from normal to red as closure increases. Since users are likely to focus more on grasped objects than on finger details [7], it is interesting to consider OC as an alternative to FC.

As with FC, we consider rate, interpolation type, and closure representation. The calculations are analogous to those for FC. However, only the digit giving maximum color intensity is used to determine object color, since there is only one object being colored.

3.2.7 Arrow (AR)

In the Arrow technique, arrow glyphs emerge from fingernails of an outer hand model, growing with increasing hand closure. We include AR to consider glyph approaches and because it was seen in the work on which our grasping implementation is based [9].

We again include adjustable rate (scale), interpolation type, and closure representation. Additionally, two arrow directions are considered: normal to fingernails or parallel to penetration vectors, where the penetration vectors point between outer hand digit tips and corresponding inner hand tips. The difference is shown in Fig. 4. Arrows are red, with 0.2 cm body cylinder radius, 0.5 cm head cone radius, and 0.4 cm head cone length. Body cylinder length is computed as $s_a \cdot i_n \cdot R$, where s_a is scale and the other terms are as in Section 3.2.5. The arrow origin is centered under the fingernail such that the tip is just below the surface at zero finger penetration.

3.2.8 Vibration (VB)

Vibration visually vibrates segments of an outer hand model. This affects visual hand appearance only and does not affect the grasped object or simulation. The vibration might be disturbing for users, but, considering positive effects of visually-disturbing IH [10], this may discourage closure, inducing light touch for grasp training.

We consider variations of VB generated by different joint angles, amplitude- vs. frequency-based closure representation, and scale parameters (s_{va} for amplitude, s_{vf} for frequency).

Per contacting finger, we visually offset one joint angle (selected in first study) by adding angle $r(t)$ for rendering:

Amplitude-based: $r(t) = i_n \cdot s_{va} \cdot \sin(s_{vf} \cdot 2\pi \cdot t)$, (2a)

Frequency-based: $r(t) = s_{va} \cdot \sin(i_n \cdot s_{vf} \cdot 2\pi \cdot t)$, (2b)

where t is time elapsed (sec) since finger contact began.

4 Design Study

4.1 Overview

Before the main study, we conducted a design study of technique parameters. Subjects adjusted parameters for visual cues while picking up and dropping a virtual ball in an environment similar to Fig. 5. IH and OH were not included in this stage because they are not adjustable.

4.2 Subjects

Note that it was not our intent in this stage to do extensive optimization. Instead, the purpose was to identify reasonable parameters, avoid bad settings, and gain preliminary insight into the techniques. For such purposes, a small number of subjects is sufficient [33]. We recruited 5 subjects with mixed experience levels. Two of them had substantial VR experience and knowledge about the grasp sticking problem, although they had not tried these specific visuals and parameters. The other subjects had no VR expertise.

4.3 Apparatus

Subjects reached into the mirror-based 3D display in Fig. 6. An Acer GD235HZ LCD showed 1920 x 1080 images at 120 Hz, viewed with NVIDIA 3DVision glasses. A mirror reflected the LCD, with a polarizing sheet addressing interactions between polarization of the LCD and glasses. The head was not tracked – we noticed only minimal head motions when developing experiment tasks. An 18-sensor CyberGlove tracked finger joints, with missing distal joint angles computed as two thirds of middle knuckle angles. An Ascension miniBird 500 tracked the palm. Desktop speakers played audio feedback. Subjects adjusted parameters using a Griffin PowerMate knob without stops or reference points. The PC was a Dell Precision T5500 with a Xeon W3680 3.33GHz processor, 12 GB Ram, and an NVIDIA Quadro 5000 graphics card.

4.4 Design Study Procedure and Results

For clarity, we present per-technique procedures and results in an interleaved manner. We present the relevant results, with some secondary details abbreviated when they do not impact choices. We did not find any notable difference between experienced and novice subjects.

4.4.1 Background Procedure

The CyberGlove was calibrated per subject using reference poses aided by foam wedges. Subjects then practiced grasping and releasing a 5.25 cm-radius ball with OH. During this training, subjects were asked to observe the sticking object problem and were shown that light touch reduces the problems. Subjects were asked to tune the visual techniques to encourage light touch, for each of the techniques in the order below. In addition to tuning the parameters, whenever choosing between discrete rendering options, subjects were asked to rate their preferences as weak, medium, or strong.

4.4.2 ST Procedure and Results

Subjects adjusted ST alpha between 0.0 (transparent) and 1.0 (opaque) by rotating the knob. The value was hidden from subjects. Subjects indicated lowest-good, highest-good, and overall best values.

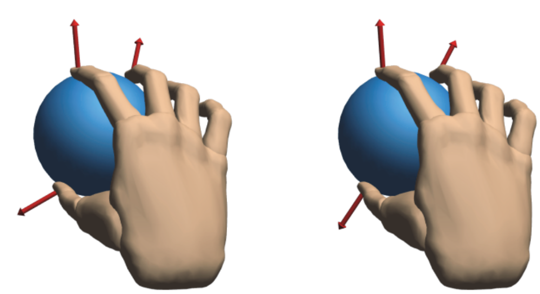

Fig. 4. Arrow directions: fingertip normal (left) and penetration (right).

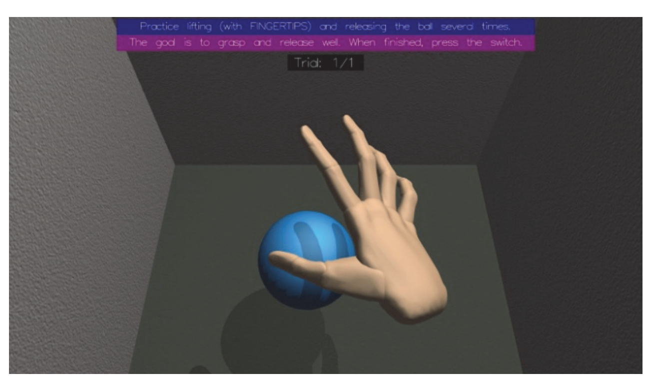

Fig. 5. Ball-drop environment for familiarizing subjects with grasping.

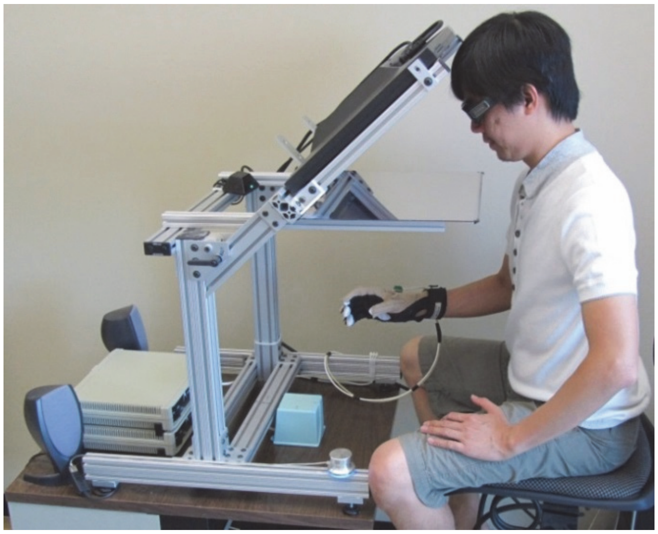

Fig. 6. Equipment for our studies.

The mean of subjects' "lowest good" alpha values was 0.33 and the "highest good" mean was 0.86. All values in the range [0.51, 0.79] were good for all subjects. The "overall best" mean was 0.65 after omitting one unusual value from a subject who preferred full transparency (0 alpha) but stated any value up to 0.96 was good. No other extremes occurred.

Overall, alpha should visually differ noticeably from 0 and from 1, with acceptability of a range of values.

4.4.3 2H Procedure and Results

Stage 1 (preparation): Subjects tested all 12 variations of 2H, pressing the knob to cycle.

Stage 2 (rendering type): Subjects were shown an inner ghost with see-through and were asked to rank the 3 render styles while switching between them (colored-semitransparent, wireframe, skin-semitransparent).

Four subjects gave the following best-to-worst ranking: wireframe, colored, skin. These subjects rated their preference level as strong, with one subject commenting that they preferred the ghost to look very different than normal. The fifth subject ranked in the order: colored, wireframe, skin, with medium preference.

Stage 3 (ghost position): Subjects were shown a ghost with see-through in their preferred rendering style. They cycled between inner and outer ghost and specified their preferred ghost position.

Four of the five subjects preferred inner ghost, with preference level balanced between medium and strong.

Stage 4 (inner visibility): Subjects were shown their preferred ghost position and rendering style. They cycled between visibility conditions and specified their preferred visibility (see-through or opaque). All subjects preferred see-through.

4.4.4 FC, OC, and AR Procedures and Results

We consider aspects of FC, OC, and AR in aggregate, as we choose final mapping type and closure representation to be the same throughout the main study. The FC, OC, and AR sessions shared the following three stages:

Stage 1 (scale): Subjects adjusted scale parameter (value hidden) with linear mapping to set best value. Subjects then adjusted scale twice more, for superlinear and sublinear, being instructed to tune for "similar experience".

Average tuned scales for the linear mapping were 1.0 for FC, 1.31 for OC, and 1.06 for AR. For FC, this spreads color change over a 5.25 cm penetration range. For OC, the effect is slightly more sensitive. For AR, arrow length closely matches penetration distance.

Superlinear mapping scales were 1.1 for FC, 0.99 for OC, and 0.9 for AR. Sublinear mapping scales were 1.3 for FC, 1.21 for OC, and 1.53 for AR.

Stage 2 (mapping): Subjects cycled between the 3 mappings (each using its tuned scale from Stage 1). Subjects ranked the mappings.

Linear was ranked best 6 times (3 in FC, 2 OC, 1 AR), superlinear best 5 times (2 FC, 1 OC, 2 AR), and sublinear best 4 times (2 OC, 2 AR). Preference level and other rank orders showed no clear pattern, except that there were no strong preferences in AR. Overall, nonlinear mapping was not found better than linear, so we selected linear.

Stage 3 (representation): Subjects were shown their preferred mapping and cycled between the two closure representations (penetration and force) to identify their preference. For FC and AR, subjects were advised to notice color/arrow length balance between thumb and fingers (affected by representation choice, see Section 3.2.5).

For FC and AR, penetration was preferred to force by all subjects, with medium and strong preference levels. We observed that penetration provided more balanced feedback between digits for subjects' grasp choices. For OC, 3 subjects preferred penetration, and the two subjects preferring force expressed weak preference level.

Extra Stage for AR (arrow direction): The AR session had subjects try the two arrow directions and indicate preference (fingernail-normal or penetration).

3 subjects preferred penetration-parallel arrows over fingertip-normal arrows, with two noting strong preference. The other two subjects had mixed preference levels (medium, strong).

4.4.5 VB Procedure and Results

Stage 1 (finger joint): Subjects ranked four finger joint angles for vibration, cycling between MPJ-flexion, MPJ-abduction, PIJ-flexion, and DIJ-flexion. Thumb vibration was disabled in this stage.

2 subjects ranked MPJ-flexion as best (medium, strong), 2 chose PIJ-flexion (medium, strong), and the fifth chose MPJ-abduction (medium). None chose DIJ-flexion. We decide to favor MPJ-flexion over PIJ-flexion for two reasons: MPJ is visually more consistent with the inner thumb joint choice described next, and subjects' second-best choices reflected MPJ more often than PIJ.

Stage 2 (thumb joint): Thumb vibration was enabled and finger vibration matched the Stage 1 preference. Subjects specified preference between two thumb vibration angles. For visual consistency with finger vibration, the options depended on Stage 1 results. The options were TMJ-roll and TMJ-abduction if Stage 1 preference was an MPJ angle. Otherwise, they were MPJ-flexion and IJ-flexion.

TMJ-abduction was preferred by 2 subjects. The other three angles were preferred by 1 subject each. TMJ-abduction is similar to a finger's MPJ-flexion in terms of both joint distance from tip and tip motion primarily normal to object surface.

Stage 3 (amplitude scale): Using their preferred joint angles and amplitude-based vibration, subjects adjusted s_{va} and s_{vf}. Subjects switched between the two parameter adjustments by pressing the knob.

For amplitude vibration, the mean tuned scale values were s_{va} = 12.6 and s_{vf} = 9.04. Values varied widely, with range [2.5, 26.5] for s_{va} and [2.4, 19.0] for s_{vf}.

Stage 4 (frequency scale): Subjects repeated Stage 3-type tuning for frequency-based vibration, with instructions to tune for "similar experience".

For frequency vibration, the mean tuned scale values were s_{va} = 7.1 and s_{vf} = 12.4. Values varied widely, with range [1.0, 21.0] for s_{va} and [6.0, 20.0] for s_{vf}.

Stage 5 (vibration type): Subjects chose between amplitude-based and frequency-based vibration while reviewing their tuned settings.

4 subjects preferred amplitude-varying vibration to frequency-varying vibration, with medium-to-strong preference levels. The remaining subject had medium preference for frequency.

5 Main Evaluation of Techniques

5.1 Design

We conducted within-subjects experiments to evaluate the 8 visual techniques objectively and subjectively. All technique parameters were set according to the design study above, using mean tuned values for continuous parameters and most-often-chosen best settings for discrete parameters. For consistency, the same mapping type (linear) was used in all affected techniques. For VB, MPJ-flexion and TMJ-abduction were used as explained in Section 4.4.5.

The first session was a targeted ball-drop to measure grasping performance. The independent variables were:

1. *Visual technique* – OH, IH, ST, 2H, FC, OC, AR, and VB.
2. *Ball size* – small (4 cm radius) and large (6.5 cm).

The dependent variables were:

1. *Penetration depth* – real finger penetration into ball.
2. *Release time* – time taken to release the grasped ball.
3. *Translation error* – ball translation resulting from release (release-imparted motion).

Next, a technique ranking experiment had subjects rank the techniques subjectively based on visual appearance, behavior effect, and overall preference. This and the following sessions used a medium ball (5.25 cm radius).

Finally, a technique explanation session sought further insight by asking subjects to explain what they liked or disliked about each visual technique and how the techniques affected their behaviors.

5.2 Subjects

30 subjects participated: 28 males and 2 females, aged 16 to 40 years (average 26), 28 right-handed and 2 left-handed. 25 subjects were students: 19 from computer-related fields. 5 non-students were also in computer-related fields. Experience levels were mixed: 9 participated in a prior VR experiment, 7 others reported exposure to a VR system, and the remaining 14 played video games, watched 3D movies, or took a graphics course.

5.3 Procedure

5.3.1 Procedure for General Introduction

We calibrated the CyberGlove per subject. Subjects then practiced OH-type grasping for 3 ball sizes. Per size, subjects lifted and dropped a ball several times, using fingertips (Fig. 5). Subjects could use any digits or grasp shapes they found suitable.

5.3.2 Targeted Ball-Drop Procedure

This experiment had eight trial sets: one per visual technique, in random order. Per set, subjects first practiced grasping with the technique in a ball-drop environment similar to Fig. 5. Subjects then practiced a targeted ball-drop task twice: once with on-screen instructions and once without. The instructions stated that the goal was to drop the ball from a wireframe cube above an X-mark (Fig. 7). The task is explained by its practice instructions:

1. Pick up the ball from floor and move it inside the cube. The (tick-tick-beep) countdown sound will begin.
2. Wait for the [2-second] countdown sound to end while holding the hand still.
3. Release the ball at the countdown end using "NORMAL finger release motion (not too fast or too slow)".

The cube switched from black to bright green as the ball was centered in it. The color switched at a threshold distance of 1.5 cm, which also triggered the countdown sound. The ball center was required to stay within 1.75 cm of the cube center during the countdown or the trial restarted. Premature release (between pickup and beep sound) also restarted the trial. Restarting occurred rarely and mainly from forgetting procedure.

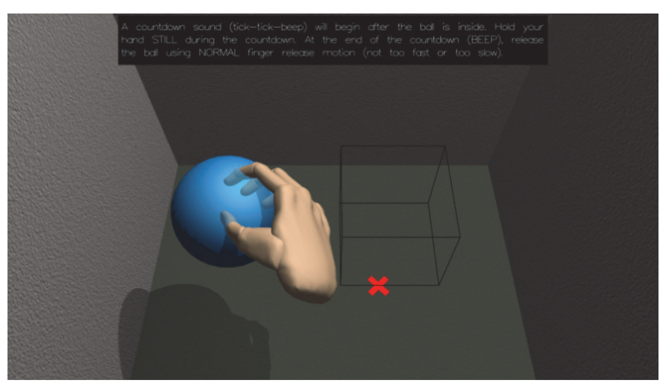

Fig. 7. Targeted ball-drop task with wireframe cube and target.

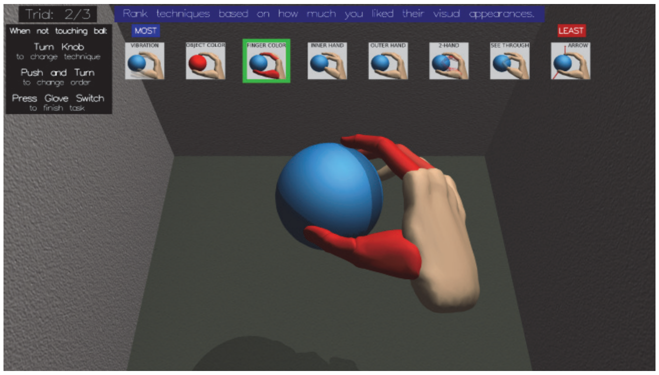

Fig. 8. Technique ranking. Subjects ordered icons representing visual techniques while freely highlighting icons to test techniques.

Per technique set, after practice trials, subjects performed 8 real trials in randomized order (4 trials for each of the 2 ball sizes).

5.3.3 Technique Ranking Procedure

Subjects performed 3 ranking tasks. Per task, subjects ordered icons representing the visual techniques from "MOST" to "LEAST" for an on-screen question (Fig. 8) while freely switching between techniques to test them. The first two tasks asked "how much you liked their visual appearances" and "how strongly they affected your behavior", in random order. The third task asked "how much you preferred them overall". Initial icon order was random per task.

Subjects rotated the knob to highlight any icon and test the highlighted visual technique. Subjects changed the position of an icon by pressing the knob while rotating. Subjects signaled the experimenter when done ranking.

5.3.4 Technique Explanation Procedure

Subjects were asked to review each technique and explain "anything you especially like or dislike about it" and to answer "Do the visuals notably affect your behavior? How?" Subjects could again browse techniques by highlighting icons with knob rotation.

6 Results and Discussion

We compare techniques to OH and IH. We especially want to identify which technique is most consistently found better than baselines, or at least provides the most promising tradeoff. Indirectly, this also gives insight into relative performance of techniques.

6.1 Results and Discussion for Targeted Ball-Drop

We computed dependent variable values, averaged over 4 trials per condition, as follows:

1. *Penetration depth*: maximum of all 5 finger penetration magnitudes at the end of the countdown, where per-finger magnitude is the distance between the tracked fingertip and spring hand tip.
2. *Release time*: time between the end of the countdown (release start) and when no spring hand fingers touch the ball (release end).
3. *Translation error*: horizontal motion magnitude (translation parallel to floor) of ball from release start to floor contact time [7].

We consider penetration depth to be the main indicator of behavioral impact. It was the most sensitive metric, with lowest within-technique dispersion (relative to across-technique). Penetration is likely a main contributor to performance effects in other variables [7], [10] and relates directly to the desired light touch.

Figs. 9-11 and Table 1 summarize results. Tables reflect pooled ball sizes, as both sizes gave similar overall patterns of technique effects. Statistical tests are nonparametric because distributions tended to be positively skewed. We used Friedman tests for overall effects and a protected least-significant difference approach (PLSD) to follow-up testing with Wilcoxon signed-rank tests. PLSD is less conservative than approaches like Bonferroni correction, but this can be mitigated by noting patterns of effects rather than isolated findings, particularly in borderline cases. PLSD is reasonable as our comparisons seek to balance between chances of false positives and false negatives, rather than mainly minimizing the former.

We treat p-values below 0.05 as significant and mention other values below 0.1 as showing "trends". Pragmatic readers should note that slightly higher p-values suggest likely, but unproven, effects, while conservative readers may prefer to discount borderline cases. Final recommendations (Section 6.4.2) comment on confidence.

Inspection of plots suggests that IH and OH provided best and worst overall performance, respectively. Considering statistical analyses, we can further categorize each technique into one of three groups based on differences from IH and OH:

1. Promising: Techniques showing the most potential: Better than OH, based on detected differences or trends, and no statistically-detected significance or trend compared to IH. Although differences from IH may be detected by more extensive experiments, they are not likely large or consistent.
2. Compromise: significance or trends of worse performance than IH, but better performance than OH.
3. Unpromising: no detected significance or trends compared to OH, but difference or trend of worse performance than IH.

Penetration depth: Visual technique affected penetration depth, $\chi^2(7) = 40.0$, $p < .001$. Techniques grouped as:

- Promising: IH, ST, 2H.
- Compromise: OC, VB, AR, FC.
- Unpromising: OH.

Penetration was larger for the large ball (median penetration 2.8 cm) than for the small ball (1.8 cm), $\chi^2(1) = 30.0$, $p < .001$. We only mention overall size effects, as per-visual testing does not add more insight.

Release time: Visual technique affected the release time, $\chi^2(7) = 14.8$, $p = .039$. Techniques grouped as:

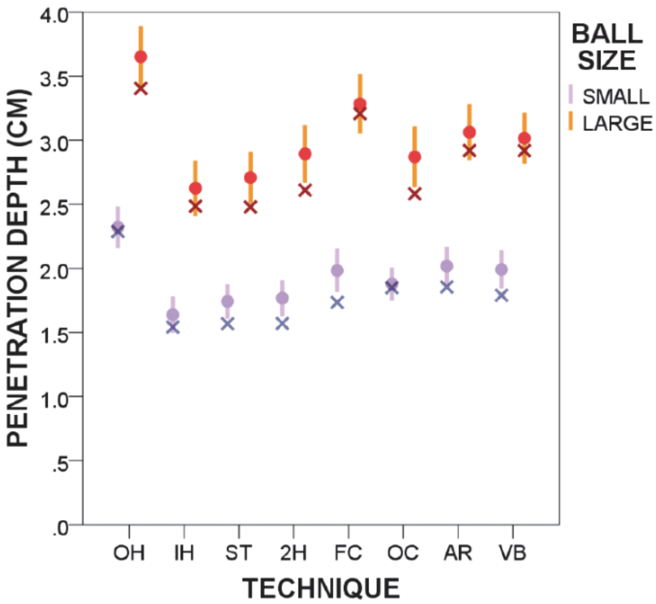

Fig. 9. Penetration depth: medians (X marks), means (circles), and standard errors (bars centered on means).

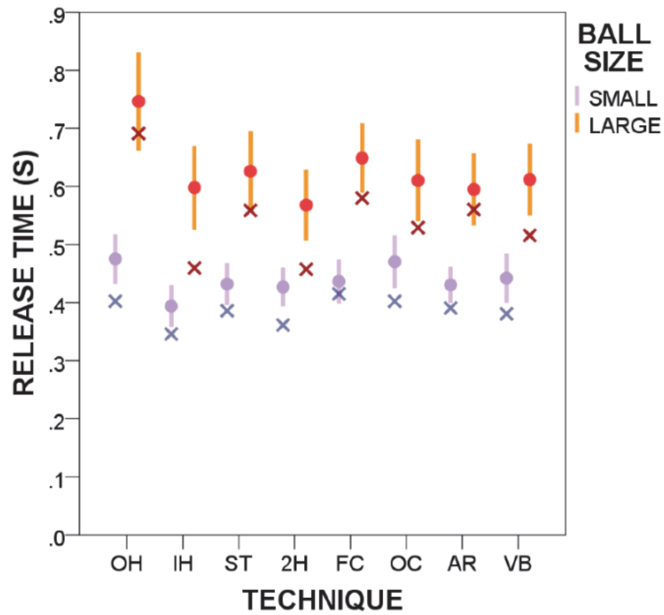

Fig. 10. Release time: medians, means, and standard errors.

- Promising: IH, VB, 2H, AR.
- Compromise: OC and ST.
- Unpromising: FC and OH.

It took longer to release the large ball (median 0.56 s) than the small ball (0.4 s), $\chi^2(1) = 30.0$, $p < .001$.

Translation error: Visual technique affected the translation error, $\chi^2(7) = 19.2$, $p = .007$. Techniques grouped as:

- Promising: ST, IH, FC, 2H.
- Compromise: OC.
- Unpromising: VB, AR, OH.

Release was less accurate with the large ball (median error 0.98 cm) than with the small ball (0.7 cm), $\chi^2(1) = 13.3$, $p < .001$.

Penetration depth was moderately correlated to release time ($r_s(1920) = .481$, $p < .001$) and to translation error ($r_s(1920) = .443$, $p < .001$). The correlation also held independently per technique as shown in Table 2.

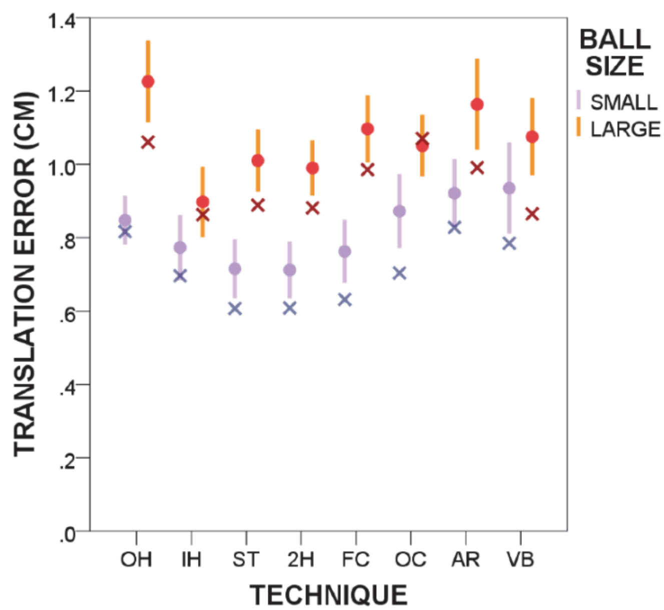

Fig. 11. Translation error: medians, means, and standard errors.

TABLE 1
PERFORMANCE RESULTS FOR THE TARGETED BALL-DROP EXPERIMENT

Penetration depth (cm)				Release time (s)				Translation error (cm)			
	Median	vs. OH	vs. IH		Median	vs. OH	vs. IH		Median	vs. OH	vs. IH
IH	1.992	p<.001**		IH	0.411	p=.031**		ST	0.784	p=.032**	p=.629
ST	2.028	p<.001**	p=.491	VB	0.432	p=.009**	p=.125	IH	0.812	p=.005**	
2H	2.150	p<.001**	p=.192	2H	0.446	p=.002**	p=.781	FC	0.826	p=.054*	p=.147
OC	2.276	p=.004**	p=.019**	OC	0.450	p=.057*	p=.099*	2H	0.845	p=.002**	p=.517
VB	2.323	p=.013**	p=.010**	ST	0.476	p=.045**	p=.082*	VB	0.872	p=.382	p=.020**
AR	2.349	p=.008**	p=.004**	AR	0.507	p=.032**	p=.644	AR	0.927	p=.861	p=.006**
FC	2.444	p=.079*	p<.001**	FC	0.512	p=.120	p=.094*	OC	0.982	p=.098*	p=.060*
OH	2.868		p<.001**	OH	0.561		p=.031**	OH	1.012		p=.005**

*Visual feedback techniques ordered by median performance, per dependent variable, from best (top) to worst (bottom). Per technique, p-values are results of comparisons to IH and OH. ** and * indicate statistically-significant differences (p < .05) and trends (.05 <= p < .10), respectively.*

TABLE 2
CORRELATION OF PENETRATION WITH TIME AND ERROR

	OH	IH	ST	2H	FC	OC	AR	VB
Time	.287	.596	.452	.499	.551	.519	.472	.343
Error	.342	.454	.394	.437	.489	.453	.491	.421

Spearman's rho correlation coefficients, $r_s(240)$. In all cases, $p < .001$.

Discussion: Less required finger extension, due to less penetration, tends to provide faster release and less sticking, which also improves release accuracy. Where time and accuracy did not exactly follow penetration, this may reflect their reduced sensitivity: reaction time differences or unexpected sticking blur release time, and palm motion at release blurs translation error. Subject comments in Section 6.3 may give insights about some correlation results. OH had lowest correlation in both time and error, which could be explained by lack of a visual cue to aid estimation of release motion required for successful release. The relatively low time correlation in VB could reflect that some subjects were confused about grasp state.

Some techniques could have additional effects on release behavior that explain mixed performance results of VB, AR, or FC. For example, some subjects reported using faster release motion in VB (see Section 6.3), which could decrease release time but could also increase error (more palm motion). Although additional experimentation can resolve this, its value is limited – these techniques did not have strong performance overall.

We give an overall summary by counting how often techniques appeared in categories above. The resulting list is also close to a penetration-only ranking. From most to least promising:

1. IH and 2H: Consistently in "promising" category.
2. ST: In "promising" twice and in "compromise" once.
3. OC, VB, AR, FC: On average, in "compromise".
4. OH: Consistently in "unpromising" category.

The most promising techniques (IH, 2H, ST) directly revealed real hand configuration rather than using indirect representations of finger penetration. Results generalize the value of showing an inner hand over augmenting an outer hand, and extend prior IH vs. OH findings [10] to show that IH and OH rank among the best and worst of several techniques. We found time differences not seen in [10], and showed performance of several techniques.

Ball size: larger finger penetration for the large ball may be due to the larger range of motion available or tighter grasps learned for larger objects that are expected to be heavier based on real-world experiences. Reduced performance with the large ball follows from increased penetration as discussed previously for visual technique. Results directly show the relationship between finger penetration and object size, speculated in [7].

6.2 Results and Discussion for Technique Ranking

Per subject and ranking question, we assigned each visual technique an integer score in range [1, 8], giving its subject-ranked position, with 8 meaning "most" and 1 meaning "least". Figs. 12-14 and Table 3 summarize results from all subjects. We again used Friedman and Wilcoxon signed-rank tests (as in Section 6.1).

Overall preference: Plots suggest overall preferences tended to follow visual appearance more than behavior rankings. Visual technique affected overall preference, $\chi^2(7) = 86.9$, $p < .001$. Comparing techniques to IH and OH groups them as follows:

1. OC and FC: Significantly preferred over OH and IH.
2. OH, 2H, and AR: no detected difference or trends compared to OH, but significantly preferred over IH.
3. ST and IH: Significantly worse than OH, but no significance or trends vs. IH (noting borderline ST result).
4. VB: Significantly worse than both OH and IH.

Visual appearance: Visual technique affected appearance rankings, $\chi^2(7) = 79.4$, $p < .001$. Comparing techniques to IH and OH groups them similarly to the overall preference, except: FC classification hinges on a trend, and ST groups with OH, 2H, and AR (preferred over IH, matching our expectation).

Behavior effect: Visual technique impacted behavior rankings, $\chi^2(7) = 51.1$, $p < .001$. Subjects believed OH affects their behavior less than every other technique. This is consistent with penetration results from the targeted ball-drop experiment showing that subjects used lighter touch in other techniques. Compared to IH, subjects believed VB and 2H affect them more. This matches our expectation about strong behavior effect of VB, but VB had more penetration than IH. The VB effect may be more complex than anticipated: wanting to avoid intense vibrations would encourage light touch, but uncertainty about grasp state might discourage it (see the next section).

6.3 Technique Explanation Results and Discussion

Table 4 and the following discussions summarize the most relevant subject responses during the technique explanation session. Subjects stated what they especially like or dislike about each technique, and any notable perceived effects of techniques on their behaviors.

OH: The most common reason for liking OH was natural or realistic visuals. The most common dislike was inability to understand grasp pressure amount, with one subject stating that too much pressure took long to release. 29 subjects stated no behavior effects, with one of them noting that OH took more time to release. The other subject checked if fingertips touch the ball during grasp.

IH: Example reasons for liking IH include that it helped with release by showing how much to extend, and that it gave information about penetration or pressure. The most common dislikes were fingers sinking into the ball and unrealistic feeling, with two subjects mentioning grasp difficulty.

The most common responses suggesting light touch were that subjects attempted to keep fingers outside the ball or visible, with one of them noting wanting to make the grasp look natural. But, four subjects stated they grasped more tightly: one stated this was to prevent slipping, another stated this was to make the hand disappear to make sure that they hold the ball, and another mentioned using faster release motion.

ST: The common positive comments on ST were appearance (e.g., seeing through looked cool) and knowing penetration amount or real hand state. Another subject liked that it helped with release by showing how much to extend. The most common dislikes were fingers going inside the ball and unrealistic experience. Comments on behavior were similar to IH, with five subjects grasping more tightly.

2H: The most common reasons for liking 2H were appearance (e.g., looked like veins or nerves) and showing real hand state or grasp force. Two subjects stated that 2H helped them estimate when the ball would release. The most common dislike was appearance, e.g., seeing two hands was confusing or visuals were complex.

The most common responses suggesting light touch were that subjects kept fingers from sinking much and that they avoided using much force. One subject also noted fingers were letting go when the mesh (ghost) disappeared. Three others related light touch to better or easier release, with one of them noting lightest touch seemed to give the most accurate release of the ball.

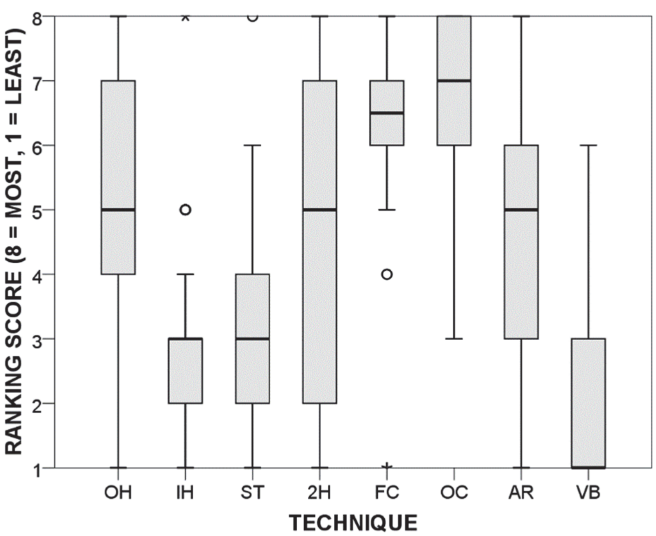

Fig. 12. Ranking scores for the “overall preference” question (box-and-whiskers plots; circles and asterisks denote outliers).

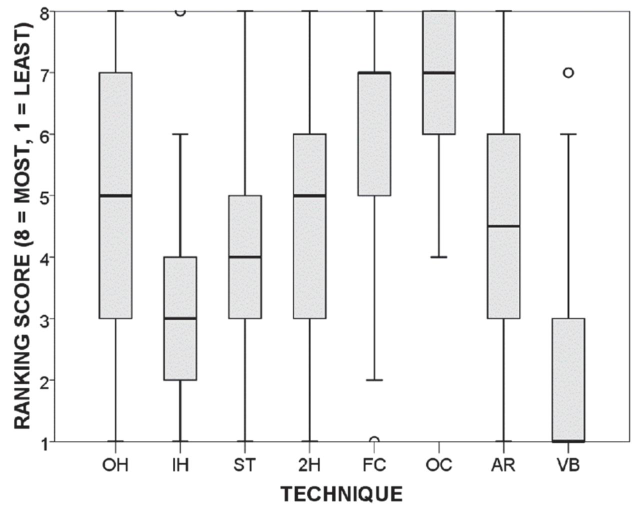

Fig. 13. Scores for “how much you liked their visual appearances”.

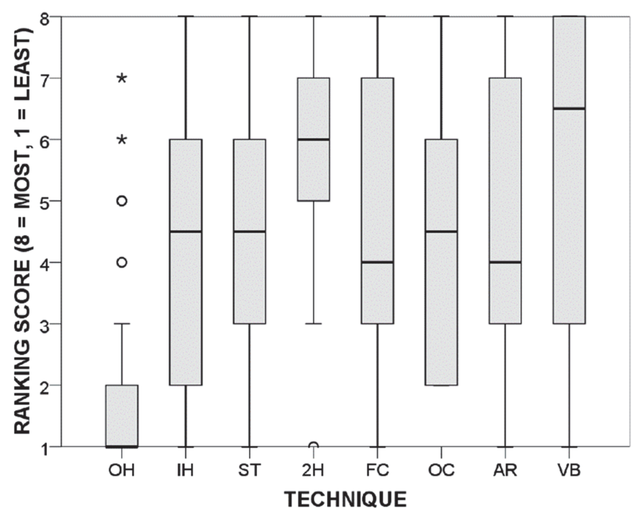

Fig. 14. Scores for “how strongly they affected your behavior”.

FC: The most common positive comment was presence of pressure feedback. One subject liked that fingers stayed on the object surface (realistic) while also showing pressure. One other noted preferring force information on the hand instead of on the object. Another noted FC helped them focus on which fingers to release. One subject disliked that finger color changes.

TABLE 3
SUBJECTIVE RANKING RESULTS FOR THE TECHNIQUE RANKING EXPERIMENT

	Overall preference				**Visual appearance**				**Behavior effect**		
	Median	vs. OH	vs. IH		Median	vs. OH	vs. IH		Median	vs. OH	vs. IH
OC	7	p=.004**	p<.001**	OC	7	p=.001**	p<.001**	VB	6.5	p<.001**	p=.055*
FC	6.5	p=.023**	p<.001**	FC	7	p=.070*	p<.001**	2H	6	p<.001**	p=.005**
OH	5		p=.001**	OH	5		p=.004**	ST	4.5	p<.001**	p=.193
2H	5	p=.885	p=.006**	2H	5	p=.975	p=.002**	OC	4.5	p<.001**	p=.934
AR	5	p=.501	p=.003**	AR	4.5	p=.455	p=.007**	IH	4.5	p<.001**	
ST	3	p=.022**	p=.100	ST	4	p=.150	p=.028**	FC	4	p<.001**	p=.548
IH	3	p=.001**		IH	3	p=.004**		AR	4	p<.001**	p=.501
VB	1	p<.001**	p=.031**	VB	1	p<.001**	p=.028**	OH	1		p<.001**

*Ranking of techniques from highest (top) to lowest (bottom) median scores, for each question. Per technique, p-values are results of pairwise comparisons to OH and IH. ** and * indicate statistical-significance differences (p < .05) and trends (.05 <= p < .10), respectively.*

TABLE 4
SUMMARY OF SUBJECT RESPONSES

	OH	IH	ST	2H	FC	OC	AR	VB
Like/ Dislike	19/4	6/19	10/14	18/7	26/1	23/1	22/6	4/26
Light touch	0/1	7/11	8/13	15/15	20/22	15/18	15/16	12/19

Like-to-dislike ratio (number of subjects stating they liked a technique over number indicating dislike) and light-touch ratio (number of subjects giving answers suggesting light touch over all subjects reporting behavior effects).

The most common responses related to light touch were that subjects aimed for light colors (two subjects noting it helps release well or precisely) and that they avoided using too much force. Two subjects also stated they balanced colors/pressures across fingers. Another also stated FC helped anticipate release. Two subjects stated they grasped tighter by aiming for red to have better grip (opposite of light touch), with one of them balancing colors across fingers.

OC: The most common reason for liking OC was presence of pressure feedback. Five subjects related color effects to grasp state. One other stated color change made them feel the touch. Another indicated preferring pressure at the object instead of the hand. Another liked that the hand retained a natural look. The subject that disliked OC stated uncertainty about meaning of some colors.

Comments related to light touch were similar to FC, with one subject noting light color allowed easy release. Two subjects grasped tighter by aiming for red to have better grip. One other adjusted grasp for color to be in the middle, stating red suggested too much grip and might break the object, and light color suggested not getting a good grip. Another mentioned grasping normally because the feedback did not tell which fingers to adjust.

AR: The most common positive comment on AR was presence of pressure feedback. One subject liked seeing pressure direction. Two others stated it helped estimate release. The most common dislikes were arrows emerging from fingertips and occlusion of some arrows.

The most common responses suggesting light touch were about aiming for short arrows (one subject noted it helps release easily and another noted also aiming for uniform arrow lengths) and avoiding too much pressure. Three subjects watched arrows during release, with one of them noting this showed when the ball was going to drop, and another noting it helped release better.

VB: One subject liked VB's uniqueness. Two others liked that it showed pressure. Another subject liked that vibration was easy to see. The main dislike was appearance (e.g., weird, unnatural, distracting, confusing). Four subjects were unsure about grasp state. Two others disliked discrepancy from the real hand.

The most common responses suggesting light touch were that subjects aimed to reduce vibration and that they avoided using too much pressure. However, four subjects stated that they grasped tighter, with one citing fear of dropping the ball due to vibration. Three other subjects mentioned change in release behavior, with one of them using faster release motion, another extending fingers more because they felt release was slow, and the other doing both.

Discussion: Mainly, subjects liked information about real hand state or grasp force but did not like visual interpenetration and vibration. Like-to-dislike rates roughly resemble overall preference ranking of Section 6.2.

The main noted behavior was light touch, suggested by proportions of related comments (light-touch ratios). The comments suggest visual cues encouraged or helped subjects understand and control light touch. The numbers of comments related to light touch in IH and ST are relatively low, considering penetration results from the targeted ball-drop experiment. A possible reason includes a visual capture phenomenon reported in [10], where subjects believed (real) fingers were open wider with constrained visuals (OH) than with penetrating visuals (IH).

Comments also indicate visual cues helped some subjects release well or anticipate the release moment.

6.4 Summary Recommendations

6.4.1 Tradeoff between Performance and Preference

OH is a standard approach to visually mimic real-world grasping. Unfortunately, it appears to be the worst performer. In contrast, IH ranks among the best performers, but it is not liked subjectively. The goal of additional visual feedback is to balance this tradeoff.

6.4.2 Most Promising Alternatives to OH

We suggest that grasp techniques use 2H when they favor performance and use OC or FC when they favor user experience (or possibly, when combined with other mechanisms that improve performance). Each of them offers notable improvement over OH. However, no technique was found to have both better performance than IH and better subjective ranking than OH.

2H has consistently promising performance. It ranks with OH in terms of overall subjective preference (above IH). The assessment does not hinge on any borderline or mixed results. A majority of subjects liked 2H, but some disliked its appearance. Future work could study more ways of rendering 2H to seek subjective improvements, e.g., using minimal line segments, outlines, or dots to reveal the inner hand. Note that the design study already chose from some alternatives. Another idea is to draw arrow glyphs from each fingertip of the inner hand to the outer hand tips to possibly encourage lighter touch. We consider 2H the best overall technique.

OC is subjectively strong (significantly higher visual and overall rankings than OH and IH, and high like-to-dislike ratio). Its performance is a compromise between OH and IH (significant for penetration effects, and trends in other performance variables). Future work could investigate more color variations to seek performance improvements. We already used best tuned scale and choice of three interpolation types, based on asking subjects to judge effects on grasp control. Objective optimization may find better performance, but could also compromise subjective quality. Combining OC with a release mechanism [7] or haptics, in cases where grasping systems allow this, may reduce any relative weakness of OC. The performance gain from that mechanism [7] exceeds performance gains reported here (vs. OH). The reduced penetration in OC (and other cues here vs. OH) would reduce side-effect release motions influenced by the mechanism.

FC gave overall similar results to OC, but with weaker support for lighter touch and visual appearance compared to OH (hinging on trends). We additionally compared FC to OC, with no additional findings (release time, $p = .393$; translation, $p = .861$; penetration, $p = .106$; behavior, $p = .206$; appearance, $p = .118$; preference, $p = .374$). Thus, aside from higher confidence in OC results, we do not recommend one over the other.

6.4.3 Remaining Visual Techniques

AR, like OC, provides a performance improvement over OH but appears worse than IH. Although AR subjectively ranked with OH, OC offers a more promising alternative.

ST may be worthy of further consideration due to good performance, but it is less liked than 2H, which also has good performance. Performance results of ST, 2H, and IH suggest that future design of additional techniques should consider different ways of revealing the inner (real) hand state directly.

VB had no advantage over IH. We speculated that VB could have unpleasant visuals but strongly encourage light touch. Subjective ranking of behavior effects shows that subjects also expected large behavior effects. However, VB performance gave mixed results, with worse penetration than IH, and VB is subjectively worse than IH.

6.4.4 Interaction Guidelines and Other Implications

Results suggest the standard 3d interaction guideline to avoid penetrating visuals, e.g., [17], and supporting work, e.g., [15], [16], should be reconsidered or updated to consider limits of applicability and capture our new results. Multiple techniques that reveal penetration are good for grasp performance, and there may be other interaction types with similar results, e.g., [22]. We propose the following alternative guideline:

Interaction techniques should provide interpenetration cues to help users understand and control interaction (e.g., for light touch). Moreover, for grasping:

- *Subjectively, certain visual cues augmenting constrained visuals are liked.*
- *Performancewise, direct rendering of interpenetration can be better.*
- *Reasonable tradeoffs can be found.*

Work comparing haptic to visual cues for grasping, e.g., [2], [11], should also be re-assessed if it did not use the best-performing visuals. Relative performance of techniques from our study provides a starting point to estimate if results would still hold.

We expect our results are applicable to other VR displays in which users observe a purely virtual environment, e.g., a head-mounted display.

In some displays where users view combined virtual and physical hands, e.g., CAVE [29], the user experience may roughly reflect 2H-type grasping. However, since the physical hand can occlude the virtual hand in some environments, AR or OC may be useful. ST results might indicate what can be expected from augmented reality grasping visuals that show physical hand state "through" virtual objects, e.g., [3], although the visuals are not exactly identical.

The prior IH vs. OH study [10] may suggest some generalization to other shapes and task. There, a penetrating hand provided good performance for precise arrangement of cube and bunny objects, while subjects preferred a hand constrained outside of objects.

Grasp simulation quality could affect user behavior, e.g., noisy sensing or poor contact simulation may cause users to grasp tighter. Visual cues may remain useful for understanding grasps. Most subjects grasped well with our system after calibration and practice.

Cue performance may degrade when the cue is occluded by hands or objects. Our studies demonstrate a common view angle and position for a grasping hand.

7 Conclusion and Future Work

A design study selected reasonable parameters for visual feedback techniques for grasping, and a main study evaluated the eight techniques. Compared to just showing a constrained hand, we can improve performance or subjective experience. The techniques giving best performance are not the same as those giving best subjective results, but reasonable tradeoffs can be found. Additionally, we observe only subjective improvements over showing only the real penetrating hand state. Based on the results, we suggest that grasping systems use a two-hand ghost technique when they favor performance, and that they use either object or finger color when favoring subjective visual quality. There may be additional aspects of subjective experience, such as subjective quality of grasped object motion, that could be more closely tied to performance.

Future work can consider possible technique improvements and a study of multimodal techniques as noted in Sections 6.4.2 and 6.4.4.

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Mores Prachyabrued received the BE degree in computer engineering from Kasetsart University, and the MS and PhD degrees in computer science from the University of Louisiana at Lafayette. He is an instructor at the Faculty of Information and Communication Technology at Mahidol University. His research interests include whole-hand interaction and virtual environments.

Christoph W. Borst received the BS degree in computer science from the University of Texas and the PhD degree in computer science from Texas A&M University. He is an associate professor of computer science at the Center for Advanced Computer Studies at the University of Louisiana at Lafayette. His research interests include 3D interaction, virtual environments, and haptics.