Stacked Retargeting: Combining Redirected Walking and Hand Redirection to Expand Haptic Retargeting's Coverage

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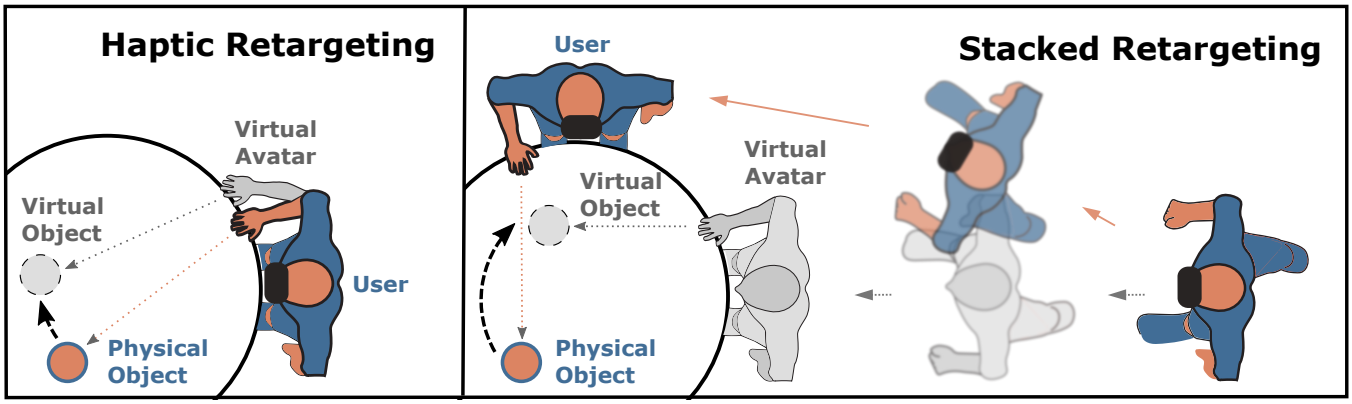

Figure 1: A top-down view illustrating (left) Haptic Retargeting and (right) Stacked Retargeting. By stacking redirected walking and haptic retargeting, we can repurpose a physical object to provide haptic feedback for a virtual object beyond the limits of haptic retargeting applied with hand redirection alone.

ABSTRACT

We present Stacked Retargeting—combining haptic retargeting and redirected walking—to maximise the use of passive proxy objects for VR haptics. Haptic retargeting work to date has considered stationary reaching and grasping interactions, and this inherently limits a proxy object's scope. We consider exactly where this reaching and grasping occurs from, to increase the potential of each proxy. We present (a) a staged approach to implementing Stacked Retargeting, (b) five redirected walking approaches that enable users to arrive anywhere at the site of interaction, and (c) a usability magnitude estimation evaluation of these techniques. We demonstrate how Stacked Retargeting can meaningfully increase the practical use of proxy objects for VR haptics without degrading the user experience.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual Reality, Haptics, Redirection

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1 INTRODUCTION

Haptic retargeting [2] has become a popular technique for adding haptic feedback, and so enhancing immersion, in VR. By leveraging visual dominance over proprioception [3, 41], haptic retargeting redirects the users' hand to enable a passive proxy (e.g., an everyday, physical object) to be used as haptic feedback for multiple virtual objects. However, this only works for small amounts of redirection before the technique becomes jarring and the user experience degrades (see e.g., [5, 7, 13, 20, 46]). Thus, for non-intrusive haptic retargeting applications, a passive proxy can only be remapped to virtual objects within its immediate vicinity [6, 7]. In practice, then, each physical proxy can only provide haptic feedback for virtual

objects within such close proximity that numerous proxies would be required to sufficiently support any interaction space.

To expand physical proxies' haptic coverage (the area where physical proxies can provide haptics without users detecting redirection), and so increase any props' utility, we turn our attention to the broader space of interaction. Haptic Retargeting work to date has considered stationary reaching and grasping interactions, and this inherently limits a proxy object's scope. If we consider and plan for exactly *where* this reaching and grasping occurs from, then each proxy has much greater potential – the haptic coverage of the proxy can effectively be shifted around the space of interaction, thus increasing its use. In turn, we then need to consider how the user arrives at that final site of interaction. To achieve this, we combine multiple styles of redirection, namely haptic retargeting *and* redirected walking.

Redirected walking decouples the user's physical and virtual walking paths, allowing us to select a specific end location for a user in the scene (i.e., at a point around the table) and have them arrive without knowing they have walked that path. By combining haptic retargeting and redirected walking, we can overcome limitations of each technique (e.g., haptic retargeting can reduce the need for locomotion and the necessary size of the physical space) and facilitate proxy-virtual object pairings that neither technique could support alone (i.e., if the distances between the edge of the table and the physical and virtual objects differs, then haptic retargeting will always be needed, regardless of where redirected walking can bring the user).

We present *Stacked Retargeting*—increasing redirection across the user's interaction space to meaningfully expand haptic proxies' coverage. We combine multiple styles of redirection, namely haptic retargeting *and* redirected walking. We describe a technique to determine candidate locations from which the physical prop can act as a haptic proxy for a virtual object. We present a range of Stacked Retargeting techniques, enabling the user to arrive at a target location, which in turn allows for the greatest possible coverage of a proxy object. We conduct an initial evaluation to (a) better understand the experience of these proposed techniques, and (b) verify whether stacking techniques necessitate new redirection limits. We discuss implications and considerations for Stacked Retargeting's use.

2 RELATED WORK

Redirected walking and haptic retargeting are well-known concepts for enhancing VR haptics. To the best of our knowledge, none have yet considered how these techniques may be used together to facilitate a richer, fine-grained haptic experience for smaller, graspable objects.

2.1 Haptic Retargeting

Haptic Retargeting [2, 6, 30] uses a physical 'proxy' object to provide haptics for multiple virtual objects. This relies on a visual-proprioceptive mismatch, where the user's real and virtual hands are gradually misaligned, to enable them to reach a virtual object and touch a (non-colocated) physical object simultaneously. This technique, however, can only be applied within a small offset range before the user notices [9–11, 15, 31, 46]. Once the user notices, their experience and performance degrades [5, 13, 20].

Esmaeili et al. [8] reported that hand movement can be scaled down by up to 0.87x and scaled up by up to 1.31x, depending on the reaching direction. Since haptic retargeting uses hand redirection within the user's reachable space, Clarence et al. [7] found that the influence of various factors on limits is generally small. They conservatively suggested that the reaching path can be rotated up to $\sim 15^\circ$ with rotation-based hand redirection to remain imperceptible when reaching in any direction.

Relying on a single redirection technique for haptic retargeting limits remapping to the immediate vicinity of a proxy; hence, numerous proxies are still required to cover the interaction space [6].

2.2 Redirected Walking Techniques

Redirected Walking [29, 33] enables walking in a virtual environment larger than the physical space. As with haptic retargeting, larger redirections while walking are noticeable and cause disorientation [34, 38]. Prior studies [12, 21, 34, 36] reported the imperceptible range of different redirected walking methods: Translation Gain can scale a user to physically walk 14% more or 26% less distance, Rotation Gain can scale a user's head turn 49% more or 20% less, Curvature Gain can curve the user's travelled path by $5.2^\circ/m$, and Bending Gain can bend a curvature path movement by up to $4.4x$ of its radius.

While initially introduced to prevent collisions with boundaries (e.g., walls), Redirected Walking has also been used to support room-scale haptics [37, 38]. Kohli et al. [19], for example, used redirected walking (specifically rotation gain) to enable one physical pedestal to represent five virtual pedestals around a space. Similarly, Langbehn et al. [22] demonstrated the re-use of a single physical table for multiple virtual tables using redirected walking along a virtual corridor.

More recently, Thomas et al. [40] introduced a framework that enables room-scale haptics and collision avoidance in response to positional shifts caused by locomotion techniques during interactions (e.g., redirected walking, teleportation, flying). Min et al. [28] applied similar concepts to redirect two users closer in a shared VR space, allowing them to experience direct haptic feedback (e.g., handshakes). They proposed a recovery algorithm that adjusts the users' walk based on their relative position and orientation to facilitate this interaction. Chen et al. [4] proposed using deep reinforcement learning to better adapt the applied redirection based on observing past states, thereby supporting the application of redirected walking to prevent boundary collisions and encourage consistency between the position of the user and an object for room-scale haptics.

These works showcase how room-scale thinking enables haptic experience. Redirected walking has been employed to support repeated use of physical tables and large props, but research has not yet considered how controlling the user's arrival location at the table may support haptic retargeting of objects on the table.

2.3 Combining Multiple Redirection Techniques

Prior work has demonstrated both redirected walking techniques and haptic retargeting being used together. In their original work on Haptic Retargeting, Azmandian et al. [2] proposed hybrid redirection that combines both world- (rotating the world around the user) and body- (de-coupling physical and virtual hand locations) redirection. A similar technique was also presented by Sait et al. [35], where users navigate through the environment by turning on the spot and virtual and physical objects are redirected together as the user turns around and performs reaching interaction. While these two techniques combine aspects of redirected walking (head-based rotation-gain) and hand-based retargeting, they have not considered controlling *walking* to arrive at the site at the best possible location for haptic interaction.

Matsumoto et al. [25] also demonstrated the use of redirected walking and hand redirection to transform a square-shaped table into a triangular or pentagonal table during a continuous single-object exploration. Our work, in line with haptic retargeting [2], focuses on remapping spatially-misaligned objects across a tabletop. Building on subtle redirected walking solutions to repurpose room-scale passive haptics [19], we seek to explore whether they can be combined with haptic retargeting to expand the haptic coverage.

3 STACKED RETARGETING

Imagine our user has an empty coffee cup on a table and we, the VR designers, wish to use this cup as a physical proxy for a vase in our application. Currently, the intended location for the vase is outside the coffee cup's haptic coverage. This means that if we were to use haptic retargeting, the user would notice the effect and their overall experience would degrade. As a first option, we could move the vase's virtual position to be closer to the coffee cup's position (or exactly at the coffee cup's position), so haptic retargeting could be supported. However, this may clash with the narrative or broader design of our VR experience. Alternatively, then, we could use Stacked Retargeting to alter our user's walking path such that they arrive at a different point around the table, bringing the virtual object into the physical proxy's haptic coverage. When the user arrives at that location, haptic retargeting can be used, without the user knowing, to facilitate the haptic feedback.

Stacked Retargeting enables broader use of physical proxies around us as haptic feedback for VR by leveraging redirection across a broader range of user movements. Originally, haptic retargeting considered a stationary user, already located at the site of interaction, and thus restricted possible movements to only reaching and head turns. VR can easily support a wider range of locomotion, which can be leveraged to control the user's approach and final location at the interaction site.

To this end, we turn to redirected walking, to bring the user to the site of interaction. On its own, redirected walking can already facilitate remapping between a physical proxy and a virtual object. However, there are challenges to its use. First, users must perform separate walking interactions to reach different virtual objects that share a physical proxy. Second, you need a large, unobstructed physical space for imperceptible redirection. Finally, there are location configurations of proxy and virtual objects that cannot be addressed through redirected walking alone. Haptic retargeting can begin to solve some of these challenges: removing the need for separate walking interactions for closely located objects, solving any remaining misalignments at the end of a walking path, providing alternatives in the presence of obstructions, and reducing the space of impossible proxy-virtual object pairings. In combination, then, applying haptic retargeting and redirected walking together provide the greatest possible scope of physical proxy objects.

3.1 Applying Stacked Retargeting

Stacked Retargeting can be applied via multiple steps of increasing complexity to solve the alignment problem between the physical proxy and virtual object. Subsequent steps expand the haptic coverage of the physical proxy but necessitate more interactions. We consider the use of Stacked Retargeting for interacting with objects on a table, though the same principles can be applied to interactions with objects in any space. We include pseudocode in our supplementary materials to implement Step 0 to 2 described in this section.

Starting Assumptions: The use of Haptic Retargeting and, by extension, the use of Stacked Retargeting requires multiple assumptions. We start by spelling out these assumptions here, to situate the constraints and boundaries of our solution. These assumptions, other than the specifics about the interaction table, are inhereted from the literature (e.g., [2, 11, 46]).

First, we assume the VR designer has a carefully designed virtual environment. Within this virtual environment, the designer intends the user to reach a known virtual object V. As users reach out to interact with the virtual object, they initiate their movements from a designated origin point, O, which is typically positioned to the right of their body for right-handed users. This origin point also reveals the centre of the user's body, B.[1] In this instance, we constrain the origin point to be in mid-air and not overlapping the table.

Second, within the physical environment, there exists a table or surface with a physical object on it. The location, P, of this physical object is known, as are the table's location and size. While Stacked Retargeting can work for tables of any shape, we discuss its use for a round table, defined by a centre point T and a radius Tr. Implementing Stacked Retargeting also requires knowledge of the physical room, including the room size and the table's relative position. For our initial presentation and exploration, we assume the space is large and the table is placed away from a wall (optimising Stacked Retargeting's use within rooms of different configurations is beyond the scope of this work).

Next, we assume the users' reaches are within the peripersonal space explored by the Haptic Retargeting literature (i.e., within the hemisphere in front of the user, with reaches of up to <= 40 cm [46]). Similarly, we assume the walking dynamics are akin to those explored in redirected walking. As such, we use the current known limits for haptic retargeting and redirected walking from the literature [7, 8, 12, 34, 36] (as detailed in the Related Work, above). Importantly, we are not considering leaning reaches, as these have

[1]The origin point can be anywhere around the body. For example, in a shooting game, it might make more sense for the origin point to be directly in front of the user. The important thing is that its location, with respect to the user's body, should be known.

not been explored in the literature to date and so their effect on the user experience is unknown.

3.1.1 Step 0: Does a Haptic Retargeting solution exist? Before we begin, we determine whether the current physical object location, *P*, can ever provide haptic feedback given our intended virtual object *V* and origin point *O*. There are some configurations where no solution is available without violating the known limits of retargeting.

To verify this, we need to consider two factors. First, we must determine whether the physical object is reachable. While the maximum reach a user can perform varies, prior work [46] has only examined reaches up to 40 cm. As such, we first check whether the physical object is within 40 cm of the table's edge.

Next, we calculate the maximum possible reach distance under redirection, as determined by the length of vector OV and scaled by the maximum reach extension. We check whether the physical object, P, is within this maximum reach distance from any edge of the table. This would allow an origin point that does not overlap the table, but can support a reach to the virtual object.

If either of these checks are false, then the physical object cannot act as a proxy for our virtual object (within current retargeting limits). If these checks pass, we move on to Step 1.

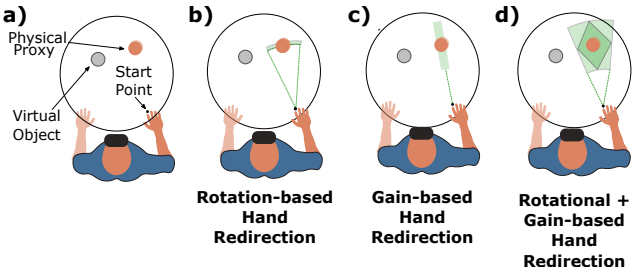

Figure 2: An illustration of haptic coverage determined by (a) the physical proxy, virtual object, and the starting point. By visualising the ranges of (b) rotation-based hand redirection and (c) gain-based hand redirection that can be applied, we can (d) form haptic coverage around the physical proxy and check if the virtual object lies within it.

3.1.2 Step 1: Calculating Haptic Retargeting. Next, we should determine whether the virtual object lies within the haptic coverage of the physical proxy. The haptic coverage is directly proportional to the length of the vector between the physical object and the origin of the reach. A *reach origin* is required to begin hand redirection. This origin point can be presented as a mid-air start button [11, 46], an object on the tabletop that a user needs to touch first [2, 6, 7], or a zone near the user that they must pass through [5]. Additionally, Stacked Retargeting presents an opportunity to have the reach origin as soon as the user arrives near the table and initiates the reach interaction. As the user reaches for the virtual object, their reach can be redirected by up to ~15° in a clockwise or counterclockwise direction [7] (Figure 2b). Their reach can also be visually extended by 1.31x or reduced by 0.87x [8] (Figure 2c). Together, this yields a diamond-shaped redirection coverage. However, we typically extrapolate that to the larger bounding area, assuming angular redirections scale with changes in the distance (Figure 2d). When the virtual object lies within this coverage, the physical proxy can be used through hand redirection alone. If the virtual object falls outside the haptic coverage, we continue to Step 2 to determine a location around the table from which haptic retargeting can occur.

3.1.3 Step 2: Determining a user location near the table for object realignment. When the virtual object falls outside the haptic coverage by hand redirection, we must apply redirected walking to bring it into alignment. We first determine the final point a user should arrive near the physical table to achieve physical and virtual reaches that are relatively similar in terms of direction and distance (within the limits of haptic retargeting). To do this, we should determine the required (1) rotational and (2) translational redirection to realign the haptic coverage (Figure 3). We refer to *rotational redirection* as the differences in the orientation that the user is facing between the physical and virtual environment, while *translational redirection* refers to the positional differences. The combination of both techniques allows for positioning the physical user at any point around the table, and so massively increases the chances that the virtual object can fall within the haptic coverage of the physical proxy.

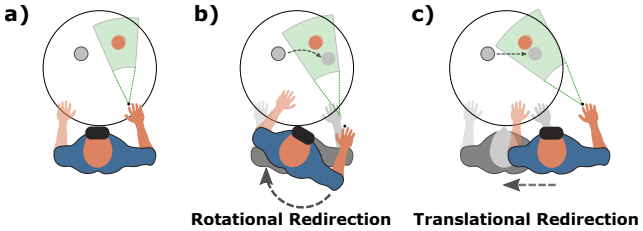

Figure 3: A figure demonstrating how (a) a virtual object (grey circle) outside of a physical proxy's haptic coverage (green area) can be aligned using (b) rotational redirection or (c) translational redirection to bring it into alignment.

We present a potential solution to determine a location near the table where the user should arrive physically, along with a new physical origin point *O'* to bring the object into alignment (Figure 4). Based on our assumption, the origin point corresponds to the position of the user's right hand when they reach the table.

First, we calculate the distance between the virtual object *V* and the initial origin point *O*. The length of vector OV is then randomly scaled within the limits of gain-based redirection. This scaling determines the potential distance at which the new physical origin point *O'* can be located relative to the physical object *P*.

In addition to the distance, we must determine the direction of the vector from the physical object to identify the new point *O'*. To find this direction (vector PO'), we used a loop that searches for a point starting from the direction of vector PO in both clockwise and counterclockwise directions. The loop continues until it identifies a location that does not overlap with the table or reaches a 180° turn from vector PO. Our aim is to find the closest location of the new origin point *O'* (that the user should physically arrive at) to the initial origin point *O*.

To determine the user's orientation at point *O'*, we subtract the direction of vector O'P with the angle formed by the difference

between vector OV and the user's orientation at *O*. We can finally use the distance and direction of vector O'P to determine the new location of the physical object *P'* in VR and see if the virtual object *V* is within its haptic coverage. Otherwise, this step will go through another loop.

Importantly here, the approach we described is based on our starting assumptions. The optimal solution will vary depending on the setup and designer's requirements. This opens up an interesting avenue for future exploration to optimise the algorithm according to different needs.

Once we determine the location needed to bring the virtual object into haptic coverage, we move to Step 3.

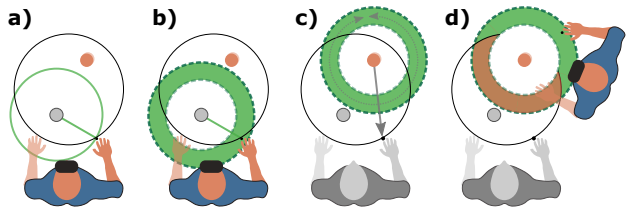

Figure 4: A figure to visualise the approach for determining a user's location near the table for object realignment. We (a) calculate the distance between the virtual object and the initial starting location, (b) outline the potential area of the new start location based on the limits of gain-based redirection, (c) move this potential area around the physical object, and (d) determine a new start location in this area where the user does not overlap with the table.

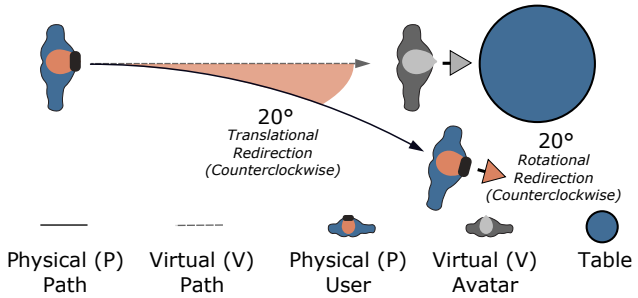

Figure 5: An illustration showing how redirected walking guides the user to different locations in the scene. When curvature gain is applied, as a redirection technique, this not only redirects the user's path, but equally redirects their orientation. Stacking redirected walking and haptic retargeting requires techniques that allow a separate application of rotational and translational redirection.

3.1.4 Step 3: Selecting and Applying a Stacked Retargeting Solution. From Step 2, we gathered information on where the user should arrive physically around the site of interaction. The next step is to redirect the user's walk, such that they arrive at that location, whilst believing they have arrived at the front of the table facing forward.

To subtly redirect the user's walk, we can apply translation, curvature, and head rotation gain. Typically, walking directly to a table would require only translation gain and curvature gain. However, these solutions apply the desired redirection equally to the user's position and direction of facing (Figure 5). With Stacked Retargeting, we may need to apply redirection between the position and orientation separately.

Hence, we propose five redirected walking solutions for Stacked Retargeting, including two **Direct** solutions: *Turn and Arc* and *Walk-while-turn*, and three **Compound** solutions: *L-Shaped Path*, *Turn-walk-turn*, and *Zigzag*.

Our *direct* solutions take a single walking path and apply rotation at either the beginning or during the walk. Our *compound* solutions, which can support larger redirections, introduce waypoints en route for additional rotational gains.

Following the literature, we use limits of $5.2°/m$ for curvature gain, scaling movement down by 0.74x or up by 1.14x for translation gain, and scaling head turns between 0.8x and 1.49x for rotation gain [12, 34, 36].

We provide a detailed explanation of each redirected walking solution in Section 3.2.

3.1.5 Step 4: Removing the Offset from Stacked Retargeting. In the previous steps, Stacked Retargeting introduces an offset between the user's physical and virtual positions. This may necessitate subsequently removing this offset for other interactions. This can be done using recovery algorithms (e.g., [28, 40]) and when the user moves to a new location, by calculating a trajectory that will enable the physical and virtual positions to come back together.

3.2 Redirected Walking Solutions

Having determined the combination of techniques necessary for Stacked Retargeting, we present our proposed solutions for both direct and compound redirected walking.

Direct Redirected Walking: 'Turn and Arc'

Direct redirected walking can be applied through a *Turn and Arc* path (Figure 6a), which builds on curvature gain. A straightforward application of curvature gain will apply equal redirection to the position and orientation of the user. To address this issue, *Turn and Arc* displaces the virtual table from its corresponding physical table. This then requires the user to make an initial turn to face the table. Once they are facing it, their walk can be redirected with curvature gain to get the user to approach the physical table with the required rotational and translational redirection.

While typically no rotation gain is introduced when the user initially turns to face the table, this solution can be combined with head rotation gain to resolve large misalignments between proxy-virtual object pairings or to reduce the perceived turn needed.

Direct Redirected Walking: 'Walk-while-turn'

Our second *direct* solution involves simultaneously applying curvature gain to the user's path and rotation gain to the user's orientation separately (Figure 6b) as the user is walking. This serves to combine the separate rotation and redirection from *Turn and Arc*

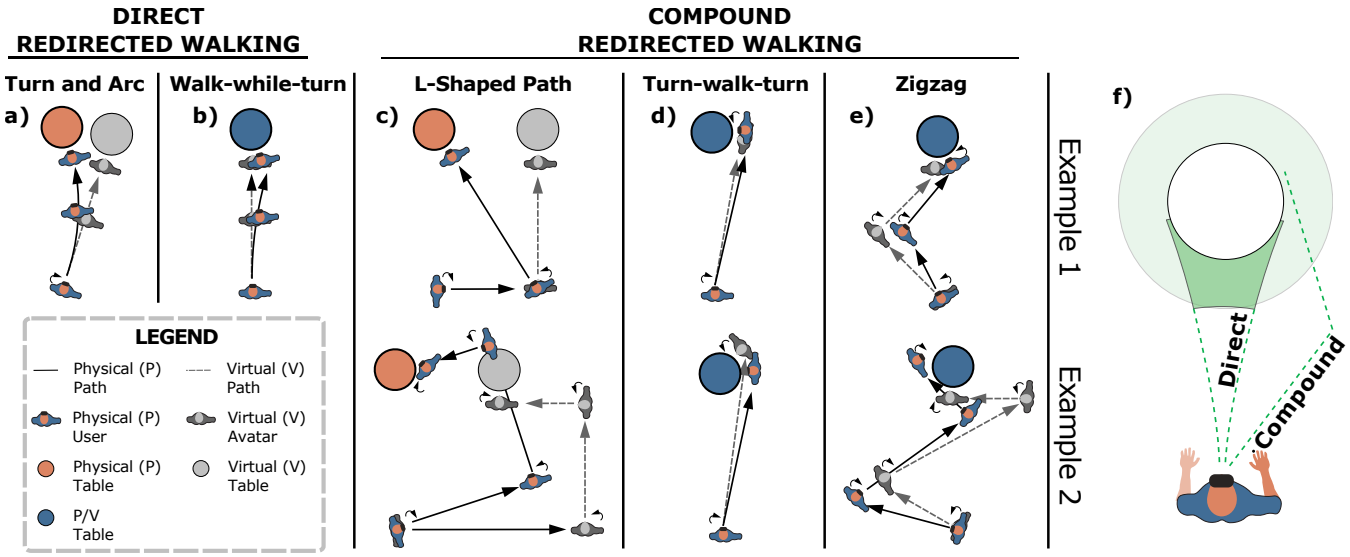

Figure 6: (a) to (e) Examples of the walking path when each proposed redirected walking solution is applied. (f) With compound redirected walking, we can get you anywhere around the site of interaction, maximising the scope of haptic proxies. Conversely, the imperceptible range of Direct Redirected Walking is limited to the distance required to approach the table.

into a synchronous redirection. This combination removes the need for a forced rotation at the beginning, giving users the impression of approaching the table straight. However, it may result in a non-typical walking style. In an extreme scenario, where large amounts of redirection are applied in the opposite direction to the user's path and orientation, it would lead the user to walk in a crab-like style. As such, we only propose this solution for small amounts of redirection.

Compound Redirected Walking: 'L-Shaped Path'

Rather than continuously applying curvature gain during walking, the *L-Shaped Path* introduces a waypoint on the route to the table (Figure 6c). This introduced waypoint necessitates the user to turn, presenting opportunities for applying head rotation gain. Depending on the destination, (1) head rotation gain can be applied as the user turns in the initial position and/or at the waypoint to face the table, together with (2) translation gain during the walk to the waypoint and/or table. The VR waypoint ideally should be positioned perpendicular to the vector from the user's walk origin to the table, forming an L-Shaped path. This introduces a misalignment between the positions of the virtual and physical tables.

Since the *L-Shaped Path* leverages head rotational gain, it enables redirection of up to 1.49x more than the virtual rotation during waypoint turns, supporting Stacked Retargeting to address large misalignments between proxy-virtual object pairings. Smaller redirection generally requires a single waypoint for imperceptible user redirection. However, incorporating multiple waypoints along the path allows for a larger redirection (Figure 6c example 2).

Compound Redirected Walking: 'Turn-walk-turn'

We designed *Turn-walk-turn* as an alternative approach to use head rotation gain (Figure 6d). Rather than walking directly to the nearest point on the table, this solution requires the user to walk to the other side of the table, providing an opportunity to apply head rotation gain as the user turns to face the table. For a small redirection, the *Turn-walk-turn* approach applies rotation gain twice: (1) at the starting point when the user turns to face the endpoint, and (2) at the endpoint when the user turns to face the table. It is also necessary to apply translation gain when any positional difference is required between the user and their VR view. When larger redirection is required, this solution will necessitate waypoints en route.

Compound Redirected Walking: 'Zigzag'

Zigzag uses head rotation gain by introducing waypoints placed along the user's path (Figure 6e). Unlike *L-Shaped Path* and *Turn-walk-turn*, this solution enables users to reach the nearest table point from the origin without any positional misalignment to the table. The solution redirects users during body turns at each point (i.e., origin, waypoints, and endpoint).

The *Zigzag* waypoint's configuration affects the required turning angle. For instance, users can make a 45° turn at the origin and endpoint. When the virtual waypoint depth position is placed halfway between the walk's origin and endpoint, its horizontal position can be calculated with a right-angled triangle. The physical waypoint's location can vary, but it affects the required final physical turn. One method to determine this location involves designing a vector from the physical endpoint that parallels and matches the vector's length between the virtual waypoint and virtual endpoint. Thus, translation gain is applied only between the origin and waypoint. Similar to prior compound solutions, large misalignments between the physical proxy and the virtual object locations necessitate a more complex path with multiple waypoints for imperceptible redirection (see Figure 6e, example 2).

4 PRELIMINARY EVALUATION

While it is known that applying redirected walking and haptic retargeting individually under the perceptual threshold has minimal impact on the user experience (e.g., [7, 8, 34, 36, 46]), it is unclear whether stacking redirection techniques will degrade the user experience and, in effect, require the development of its own perceptual limits. Our preliminary evaluation (1) assesses the effect of stacking multiple redirection techniques all within the perceptual limits on the user experience, and (2) quantifies the impact of different redirection techniques on walking dynamics so that VR designers understand the relationship between haptics and user interaction. Our supplementary materials include additional details on the evaluation and results.

4.1 Design and Apparatus

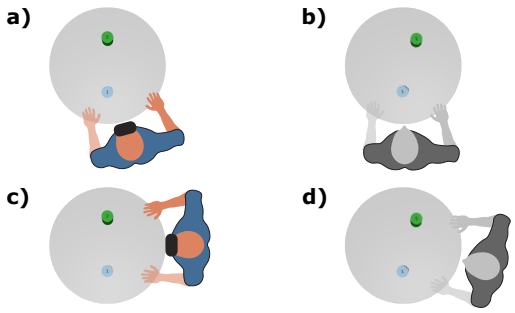

Figure 7: Illustrations depicting the designated endpoint of the walk in this evaluation. (a) shows a user standing 15° away from (b) their VR position, with the table as the origin point. All trials used this configuration, except for the *Turn-walk-turn* trial. (c) and (d) show the configuration used for the *Turn-walk-turn* trial, with the same 15° offset. The blue cylinder on the table represents the first target the user needs to touch, while the green cylinder is the subsequent target they need to reach.

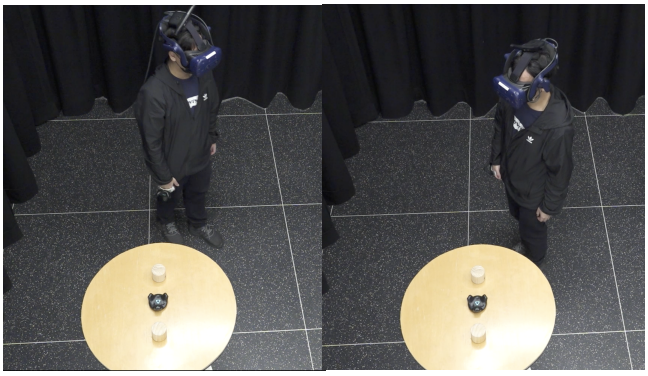

Figure 8: An example of a user approaching the table with redirection.

We employed a within-participants design, and each participant experienced all five Stacked Retargeting's redirected walking solutions. As each solution requires the user to walk a different path, participants experienced each solution first *without* and then *with* redirected walking to familiarise themselves with the path and evaluate their *with redirected walking* experience relative to it. In total, each participant experienced 10 trials (5 Redirected Walking Solutions x 2 Absence/Presence of Redirected Walking). Across the trials, all the walking and hand redirection techniques used were within the reported perceptual limits (from [7, 12, 34, 36]).

As our primary interest was to explore the impact of stacking retargeting techniques within these known limits on user experience, we displaced the virtual target object 15° from the physical proxy, which is around the limits of rotation-based hand redirection. As we use the proposed limits of haptic retargeting by Clarence et al. [7], we closely follow their user study's setup by using another physical prop as the start location. To accommodate this setup of having a fixed physical start location on the table and demonstrate Stacked Retargeting, we chose to use a fixed physical endpoint of the walk around the table, 15° rotational and translational redirection from the table's centre point (Figure 7). Overall, our study demonstrates the remapping of a second physical object on the tabletop to a virtual counterpart 22.5° away, all within the perceptual limits.

We ran the study in a space with a size of 4 m × 5 m. For the setup, we used an HTC Vive Pro head-mounted display (HMD) with a Vive Wireless Adapter to move around the room easily. Vive Base Stations were used to track the participants' movements. We tracked the participant's dominant hand with a Vive Tracker secured by a Velcro strap at the back. As our study involved tabletop interactions, we set up a round table with a diameter of 70 cm and a height of 1 m. Two wooden cylinders were placed on top of the table, one 15 cm behind the centre point of the tabletop and another 15 cm in front of it, which allows for a 30 cm reaching interaction. Following prior Haptic Retargeting studies [2, 11], these cylinders served as haptic proxies for the virtual targets (Figure 8). To calibrate this physical setup, we placed an additional Vive Tracker at the centre of the table.

4.2 Participants

Eighteen participants (8 males and 10 females, ages 19 to 33, 168.82± 9.14 cm tall) participated in our evaluation and were rewarded with a AU$20 voucher. All participants reported they were right-handed and had normal/corrected-to-normal vision. Participants reported their VR/AR experience on a semantic differential scale from 1 (no experience) to 5 (strong experience) ($Mdn = 2$).

4.3 Measures

For each trial, we collected participants' walking features to assess the impact of different redirection techniques on walking dynamics. We also capture the user experience of the solutions on each trial (both *with* and *without* redirected walking trials) with usability magnitude estimation [27]. This allows participants to rate their experience with any positive numbers (including decimals and fractions), rather than a fixed scale with pre-defined maximum and minimum. As such, participants can report relative differences they felt across experiences. Participants were asked to respond to eight questions about (1) their perception of whether what they did in the real world mirrored what they did in the virtual environment, (2) walk agency, (3) hand agency, (4) hand ownership, (5) discomfort,

(6) disorientation, (7) effort, and (8) frustration. Questions 7 and 8 are adapted from NASA-TLX [14].

After experiencing each redirected walking solution, participants were also asked whether they perceived the same calibration between the *with* and *without* redirected walking trials through a semantic-differential question ranging from 1 (Calibration felt very noticeably different) to 7 (Calibration felt the same).

4.4 Procedure

Upon providing consent and demographic information, we familiarise participants with usability magnitude estimation practice task following Turpin et al. [43], during which they rated the length of three horizontal lines one at a time. Subsequently, participants engage in VR-based training to familiarise themselves with the evaluation's tasks. This involves walking 2 m to a table and performing a reaching task without redirection. This phase is repeated twice, followed by participants completing the questionnaires in Section 4.3.

4.4.1 Task. Each participant completed 10 trials, and the entire study lasted approximately 1 hour. Each trial involved walking and reaching tasks while seeing the VR environment from a first-person perspective. The participant's right hand was represented with a virtual hand as a visual cue for interaction with objects.

In the walking task of each trial (Figure 8), participants (1) walked to a calibration point upon wearing the headset, (2) walked to the starting point (where redirection begins upon passing this point for *with redirected walking* trials), (3) walked following the instructed path to reach the endpoint of the walk, and (4) turned to face the table. At the walk's starting point, the user initially stands 3 m away from the table. A green beam lit up from the ceiling to the floor to indicate the next walking point. The participant then performed a reaching task with the palm of their dominant hand, where they (5) touched the first object and (6) reached for the second object on the table 30 cm away (Figure 7). The trial is completed then. In *with redirected walking* trials, both redirected walking and haptic retargeting are applied to realign the tabletop objects to their physical counterparts for haptic feedback (Figure 3). Finally, they report their experience as described in Section 4.3.

5 RESULTS

5.1 Subjective Experience with Usability Magnitude Estimation

Analysis — We follow the preprocessing steps described by McGee [27], which uses geometric averaging to bring all participants' responses into the same scale for statistical analysis. We excluded the *without redirected walking* trials from this analysis. These trials do not achieve the same goal as the *with redirected walking* trials that provide haptic feedback at the reach's end. These two conditions cannot be compared directly as they do not facilitate the same haptic experience. Instead, we used the collected data from the *without redirected walking* trials as a baseline when objectively comparing against trials *with redirected walking* in Section 5.3's Naturalness of Walk.

Results — Upon verifying with histogram and Shapiro-Wilk test, we could not assume normality in all cases at $\alpha = .05$. We performed a Friedman test on each measure to determine the overall effect of the Stacked Retargeting's redirected walking solutions. We found significance ($p < 0.01$) between Stacked Retargeting solutions to (1) the users' perception of whether what they did in the real world mirrored what they did in the virtual environment, (2) Walk Agency, (3) Discomfort, (4) Disorientation, (5) Effort, and (6) Frustration. We observed consistent Hand Agency ($p = 0.47$) and Hand Ownership ($p = 0.9$) across the Stacked Retargeting solutions, implying that redirected walking solutions do not influence participants' sense of agency and ownership of their hands.

We conduct pairwise comparisons using Wilcoxon signed-rank tests with Bonferroni correction to follow up on measures showing significance (Figure 9a to h). While we observe a main effect of Stacked Retargeting solutions on effort, no significant pairwise differences are found. Among the remaining solutions, *Walk-while-turn* consistently receives the lowest rating and shows significant differences when compared with other solutions. A similar trend is observed for disorientation, but no significant differences between the Direct Redirected Walking solutions: *Walk-while-turn* and *Turn and Arc*, which both involve continuous head rotation during walking. This suggests that curvature gain is more disorienting compared to compound solutions that apply redirection only at specific turning points along the path.

5.2 Perception of VR Calibration in the presence and absence of Stacked Retargeting

A Friedman test revealed a significant effect on this measure ($p < 0.0001$) (Figure 9i). *Walk-while-turn* was again rated significantly worse than all solutions. All *Compound* solutions are consistently rated the same between *with* and *without* redirected walking trials, which further confirms that Stacked Retargeting solutions built on head rotation gain are less perceptible than curvature gain.

5.3 Walking Features

Analysis — We preprocessed the walking data for each trial to begin when the user is at the starting position until they arrive at the designated endpoint while facing the table. We verified using histogram and Shapiro-Wilk test that our analysed walking features do not meet the normality assumption at $\alpha = .05$, except for walking speed.

Walking Time, Total Movement, and Total Changes in Yaw Rotation — Friedman tests reveal significance among Stacked Retargeting solutions to Walking Time, Total Movement, and Total Changes in Yaw Rotation ($p < 0.0001$). The order of the results confirms that time to be a subject of the additional movements introduced by each solution. As expected, *Direct* solutions were the fastest and required the least movement because participants walked in a straight path from the origin to the nearest point on the table from the origin.

The following table provides the medians for each solution on all these measures, sorted from the fastest with the least movement to the slowest with the most movement:

Figure 9: Distribution of each measure evaluated from the user study. (a) to (i) are the subjective measures, which are responses to the usability magnitude estimation tasks and the calibration question. (j) to (m) are the walking features.

Rank	Solution	Time	Movement	Rotation
1	*Walk-while-turn*	6.02 s	3.12 m	55.4°
2	*Turn and Arc*	6.44 s	3.15 m	80.1°
3	*Turn-walk-turn*	8.03 s	3.87 m	166°
4	*L-Shaped Path*	11.37 s	4.40 m	260°
5	*Zigzag*	11.94 s	4.82 m	264°

Walking Speed — We analyse each trial's average speed by calculating the total movement (m) divided by time (s). Mauchly's test showed a violation of sphericity ($W(0.258)$, $p < 0.05$). A one-way repeated ANOVA with Greenhouse-Geisser corrections reveals a significant effect between different solutions on participants' walking speed ($p < 0.05$). Paired t-test with Bonferroni correction revealed that the average walking speed is significantly higher in *Turn and Arc* ($M = 0.48\ m/s$, $SD = 0.09\ m/s$) than *L-Shaped Path* ($M = 0.41\ m/s$, $SD = 0.07\ m/s$) ($p < 0.001$) and *Zigzag* ($M = 0.43\ m/s$, $SD = 0.06\ m/s$) ($p < 0.05$). Additionally, *L-Shaped Path* is also significantly slower compared to *Turn-walk-turn* ($M = 0.47\ m/s$, $SD = 0.09\ m/s$) ($p < 0.05$). While the mean walking speed of *Walk-while-turn* is the highest ($M = 0.49\ m/s$, $SD = 0.14\ m/s$), pairwise comparisons of it to other solutions were non-significant, with the standard deviation of each participant's speed varying the most for this solution.

Naturalness of Walk — To assess the naturalness of walking with Stacked Retargeting solutions, we compared the time and average speed of *with* and *without* redirected walking trials for each participant. We calculated the difference in each measure by subtracting the results from the two trials. Shapiro-Wilk test was conducted to assess normality assumption at $\alpha = .05$. The results showed that the time difference did not meet the normality assumption, while the speed difference met the normality and sphericity assumptions (checked by Mauchly's test).

A Friedman test reveals no effect across Stacked Retargeting solutions on the time difference between *with* and *without* redirected walking ($p = 0.21$). On average, redirection increases the time taken to complete the path by 1.21 s ($SD = 2.04$ s), indicating a small change. As for the speed difference, a one-way repeated-measure ANOVA revealed a significant effect between Stacked Retargeting solutions on it ($p < 0.05$). By performing paired t-test with Bonferroni correction, we found only *L-Shaped Path* (M = -0.005, SD = 0.038) to significantly have lesser speed difference compared to *Turn-walk-turn* (M = -0.091, SD = 0.098). On average, applying redirection reduces the speed by 0.046 m/s ($SD = 0.091\ m/s$), which is not a large difference. These small differences are likely an effect of users subconsciously adjusting to walking further due to the applied redirection.

In summary, stacking multiple (below perceptual threshold) retargeting techniques does not impact the user experience, with the exception of *Walk-while-turn*, where the redirection techniques are stacked synchronously. At the same time, as some Stacked Retargeting solutions require more complex walking paths, this adds time, movement, and rotation to the overall interaction.

6 DISCUSSION

Stacked Retargeting increases haptic coverage

Similar to how hand redirection limits are dependent on the reaching distance [6, 7], increases in haptic coverage with Stacked Retargeting are influenced by multiple factors, e.g., walking distance, total turns/rotation, table size, and objects' placement on the table.

Our Stacked Retargeting solutions are built on a combination of redirected walking techniques, including translation gain with curvature gain or head rotation gain. Each technique has its own perceptual limits. For example, the limits of curvature gain are around $5^{\circ}/m$, which translates to a 15° redirection when walking 3 metres, as in our evaluation. In contrast, head rotation gain allows for scaling of turns by up to 49% more or 20% less, making the solution not distance-dependent and more suitable for limited physical space. As such, future applications could rely on head rotation gain through Compound Redirected Walking to achieve greater haptic coverage.

Theoretically, Stacked Retargeting with compound redirected walking allows the user to reach any location around the table. Hence, a physical proxy can provide haptic feedback for virtual objects at any location on the table, substantially increasing their potential haptic coverage. This likely requires a large physical space to support the redirected walking and a combination of redirected walking techniques (e.g., curvature gain and head rotation gain). For example, with our L-Shaped Path, rotation gain can be applied at both the initial point and waypoint for greater haptic coverage. However, our evaluation demonstrates that even in smaller spaces, Stacked Retargeting still has a significant impact on haptic coverage.

Stacked Retargeting does not impact user experience, but may require additional interaction

Users perceive less redirection and a better user experience with *Compound* solutions: *L-Shaped Path*, *Turn-walk-turn*, and *Zigzag*. Perhaps applying head rotation gain only to certain points on the path is less perceptible than continuously redirecting the entire walk, leading to more favourable ratings. Notably, our evaluation did not use the maximum redirection possible with Compound Redirected Walking; instead, we focused on applying consistent rotational and translational redirection across all solutions.

However, the improved user experience comes with the drawback of increased movement, resulting in longer walks to reach the same table (Figure 10). Nevertheless, users perceived less effort in solutions like *Zigzag* compared to *Walk-while-turn*. This perception likely arises from users' awareness of the mismatches introduced by *Walk-while-turn*, prompting them to correct their walk to the applied redirection.

In terms of hand ownership and agency, our findings indicate that these measures remained consistent across our solutions. This implies that hand ownership and agency are not influenced by redirected walking, but rather by the technique and magnitude of hand redirection applied [7, 31].

Direct Redirected Walking is simple, but limited

Our evaluation confirms that while the use of *Walk-while-turn* allows for approaching a table in one continuous trajectory, this non-typical walking style is perceived negatively, and the established perceptual limits on curvature gain are not applicable. A smaller redirection application during *Walk-while-turn* may receive more positive ratings; however, this remains a future avenue for investigating the extent to which it can be applied imperceptibly.

Alternatively, we can apply *Turn and Arc* to maximise the potential limits of curvature gain, despite requiring an initial head turn to face the table. The turn, however, could be masked in scenarios where users are teleported from one room to another, allowing the user to be unaware of the initial misalignment to the table position.

Stacked Retargeting works beyond round tables

Tabletop interaction is a popular use case for haptic retargeting, as demonstrated by prior works [2, 7, 11, 13, 46]. As our goal is to expand the coverage of haptic retargeting, we demonstrated Stacked Retargeting within the use case of tabletop interaction scenarios. However, this technique is applicable to various interaction sites (non-tabletop interactions). For example, when the user is approaching a virtual object on the floor, we can redirect their walking path to face the physical proxy in another location, and then apply hand redirection to complete the realignment. Additionally, future work can explore applying redirection as the user bends down to grab the object lying on the floor (assuming the object is short).

We can also imagine the site of interaction the user approaches being accessible from one side (e.g., a bookshelf). Here, we can apply translational redirection to redirect the user physically to the left or right of their VR view, allowing physical objects on one end of the bookshelf to act as haptic proxies for virtual objects on another end (Figure 11a).

For non-round table scenarios (Figure 11), designers should be aware of potential edge collisions with sharp edges. Designers should apply rotational and translational redirection that brings the user away from these sharp edges. Furthermore, when determining the final user location, we need to verify that the new location (1) enables haptic retargeting and (2) does not overlap with the table. Our approach in Section 3.1.3 can be used to determine the final user location that enables haptic retargeting. However, the implementation for verifying whether this final location overlaps with the table needs to be adapted for different table shapes.

Adapt Stacked Retargeting implementation for different room setups and user deviations

Stacked Retargeting allows users to arrive at any position around the table to support proxy object haptics, but the physical space can quickly constrain this. Different room shapes, sizes, and configurations will need to take into account these constraints when calculating their Stacked Retargeting solution (Figure 12). While these constraints are likely more of a problem for the redirected walking (e.g., where certain paths cannot be taken because of collisions with furniture or walls), they may also provide problems for haptic retargeting (such as other larger objects – whether physical or virtual – in the way of an intended redirected path). There may even be certain room configurations, such as corridors or narrow

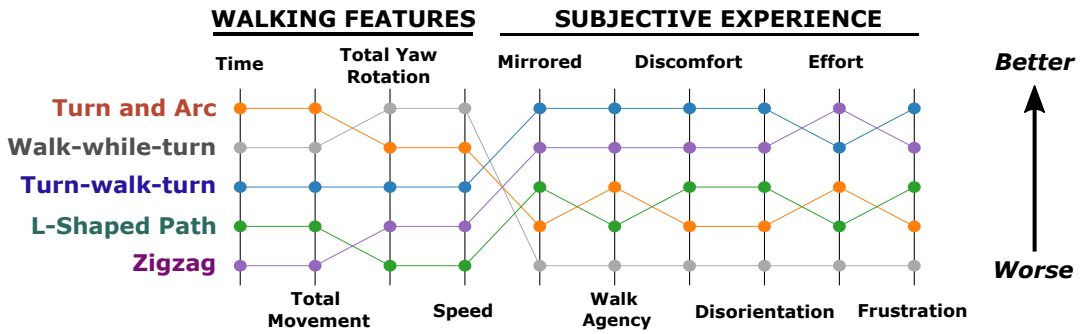

Figure 10: Ranking of Stacked Retargeting's Redirected Walking Solutions (based on means) for all measures (ranked from best to worst) from our evaluation, except for hand ownership and agency due to similar ratings across solutions (see Figure 9). A higher (or better) ranking indicates a more positive user experience.

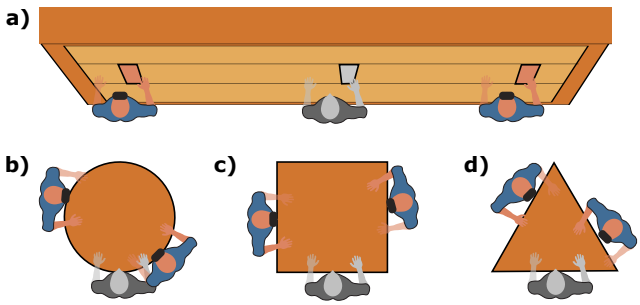

Figure 11: This figure illustrates the application of Stacked Retargeting on various interaction sites, including (a) a bookshelf, (b) a round table, (c) a square table, and (d) a triangular table. The blue avatar represents the potential user's physical location, while the grey avatar represents the user's location in VR. While round tables allow users to arrive at any point around the table, designers should be aware of potential collisions with sharp edges on tables of other shapes.

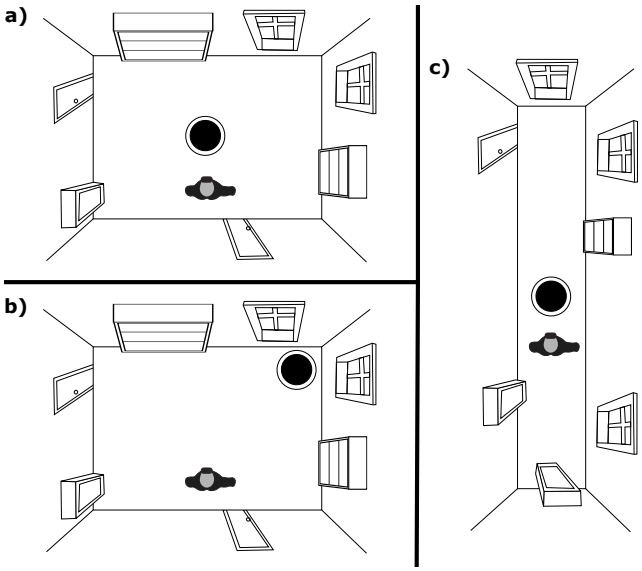

Figure 12: This figure illustrates a top-down view of the application of Stacked Retargeting in different room setups, including scenarios such as (a) a large room with the table at the centre, (b) a room with the table positioned near the walls, and (c) a narrow room.

rooms, which prevent the use of compound redirected walking entirely and necessitate the use of only direct redirected walking techniques.

Even if a specific location around a table cannot be reached, solutions may yet exist. Given the range of redirected walking and haptic retargeting (e.g., +/-15 ° for haptic retargeting alone), there are potentially multiple solutions for any given proxy location and virtual object pairing. Extending Stacked Retargeting to optimise for different spatial constraints remains an exciting avenue for future work.

While Stacked Retargeting requires designers or developers to determine appropriate paths for users to sites of interaction, there remains a chance for users to deviate from those intended paths. For example, in the Compound Redirected Walking techniques, users may veer away interim turn locations. On the one hand, this may be accounted for by simply increasing the amount of redirection being applied (where the 'limits' discussed are not absolute, but rather reflect the designers' confidence in the redirection going unnoticed). On the other hand, such deviations from the intended path may also motivate a more responsive implementation, where updates to paths and amounts of redirection are continuously monitored and updated on-the-fly.

Use narrative to keep interactions natural with Stacked Retargeting

VR applications often require users to navigate around, which provides an opportunity to expand haptic coverage through walking interactions. As walking is a common everyday activity [44], integrating it into Stacked Retargeting does not sacrifice VR's natural experience. However, Stacked Retargeting might constrain walking to follow pre-designated paths with waypoints. Stacked Retargeting can be masked with narrative and visual cues—like walking

on a bridge, simulating river currents, or tight spaces—to maintain naturalness even when interactions involved non-typical walking styles (e.g., walking sideways as a result of *Walk-while-turn*).

Additionally, Stacked Retargeting necessitates locomotion to resolve large spatial misalignment between physical objects and their virtual counterparts. Consequently, it is better suited for room-scale and tabletop-scale interactions, which involve occasional object reach interactions. While a single application of redirected walking can facilitate the remapping of a physical proxy object to a set of virtual objects within its haptic coverage [26], the user must walk away before reaching for another set of virtual objects outside of the haptic coverage. Hence, the limitations of haptic retargeting persist when VR applications primarily involve stationary reaching interactions across the tabletop with a limited set of physical objects.

Hand redirection and redirected walking may be integrated simultaneously

Our implementation of Stacked Retargeting applies redirected walking and hand redirection sequentially, back-to-back. Following prior haptic retargeting research (e.g., [2, 5–7, 11, 46]), we apply hand redirection after the user's hand touches a start button or passes through a predefined zone near the table. Thus, our work demonstrates that redirected walking can be combined with the existing hand redirection implementation to expand the coverage of haptic retargeting.

We acknowledge that this stacked retargeting implementation limits hand redirection to begin after redirected walking has been applied. However, there remains an opportunity to extend the application of hand redirection beyond tabletop interactions, as stacked retargeting leverages a broader range of locomotion and room-scale interactions. This opens up a new avenue for future research to explore the potential of integrating hand redirection and redirected walking simultaneously throughout interactions. Future work should conduct a comparison study to evaluate how different ways of linking both haptic retargeting and redirected walking, such as back-to-back and simultaneous integration, will impact user experience and haptic coverage. It remains to be seen whether applying hand redirection early as the user walks will allow larger redirections to go unnoticed by the user and expand the haptic coverage.

Stacked Retargeting can be extended and, potentially, simplified

In our initial evaluation, we demonstrated that Stacked Retargeting, through redirected walking and hand redirection, has minimal impact on the naturalness of walking, with only slight differences in time and speed. However, there are further opportunities to explore with Stacked Retargeting.

Beyond single-point retargeting (i.e., remapping a virtual object to a physical proxy), we can leverage haptic retargeting to enable closely located virtual objects to share a haptic proxy (i.e., many-to-one mapping). We can determine the designated endpoint the user will arrive at to facilitate haptic retargeting for multiple on-table objects, ensuring that multiple targets are within the haptic coverage. Consequently, this eliminates the need for users to perform separate walking interactions for each target.

Stacked Retargeting could also be combined with redirected jumping [16, 18] and change blindness (i.e., an occurrence where users cannot detect changes in the environment) [23, 32, 39, 45] to expand haptic coverage. While a prior attempt to exploit change blindness may not increase the haptic coverage provided by hand redirection [45], this effect is likely caused by the imperceptible range of hand redirection and change blindness not accumulating when applied to the same body part (i.e., hand). However, our Stacked Retargeting solution has shown that haptic coverage can be expanded without relying on applying offset to the hand. For example, change blindness can be used to realign the virtual setup closer to the physical object [24]. These potential combinations for Stacked Retargeting may simplify the trajectory required in applying Stacked Retargeting while ensuring that it remains imperceptible.

Furthermore, Stacked Retargeting can complement encountered-type haptic devices in larger room-scale interactions, such as drone-like devices [1, 17, 42] that fly around the room to provide haptic feedback for virtual objects. Future work could explore the implementation of Stacked Retargeting with these techniques to enhance VR haptics with minimal additional hardware setup.

7 CONCLUSION

Haptic retargeting provides a limited use of a physical object as a haptic proxy in VR. We proposed *Stacked Retargeting* to enable haptic feedback for virtual objects anywhere on an interaction site. We presented a staged approach to minimise redirection according to the misalignment between a physical prop and the virtual object. We then describe a technique to determine candidate locations from which the physical prop can act as a haptic proxy for a virtual object and proposed five redirected walking solutions to facilitate Stacked Retargeting. Our preliminary evaluation revealed that stacking redirected walking and haptic retargeting under the perceptual threshold does not degrade the user experience. Our insights open new avenues for future VR haptics, demonstrating how stacking redirection techniques effectively repurpose physical proxies for a larger range of virtual objects.

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