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Generalizing the Hand Redirection Function in Virtual Reality

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ABSTRACT
Hand redirection is a visuo-haptic illusion offering rich haptic feedback in Virtual Reality while using a limited number of physical objects. This technique relies on a redirection function which determines the virtual hand position depending on the physical hand position. In this paper, we extend the design space of the Hand-redirection technique by generalizing this redirection function. A user study compares 6 redirection functions. Our results suggest that the redirection function does not deteriorate the illusion offering more flexibility and control to designer over the hand trajectory and avoid collisions.

CCS CONCEPTS
• Human-centered computing → HCI theory, concepts and models; Pointing.

KEYWORDS
Virtual Reality, Haptic Feedback, Visuo-haptic Illusion, Hand Redirection

1 INTRODUCTION
Visuo-haptic illusions exploit visual dominance to enrich user immersion in virtual reality (VR). For example, users can interact with many virtual objects despite a limited number of props (physical objects) present in the physical environment [14, 22]. It is also possible to modify an object shape [1, 8] or its physical properties like weight [9, 20, 30] or stiffness [25]. When a conflict arises between sight and another sense (typically proprioception), our brain solves it by placing more trust in sight [5, 15]. Hand redirection [2, 6] is one of these visuo-haptic illusions. This technique creates a mismatch between users’ real and virtual hand on purpose. When users reach for an object, their virtual hand is offsetted from their real hand to match both real and virtual hands with the matching target. When the user touches the real object, it provides a haptic confirmation. This made-up sensory consistency between sight and touch makes it credible [18, 31]. When the mismatch between the two hand is too large, the illusion is detected by users and the immersion is deteriorated [28].

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Previous work extensively studied the influence of the distance between the virtual and the physical target on the detection of the illusion [35], but not the behavior of the virtual hand. The redirection function creates this behavior by determining the position of the virtual hand depending on the position of the physical hand. While there is theoretically an infinite number of redirection functions, previous studies rely on the same one.

In this paper, we study the design space of redirection function on their influence on the (non-) detection of the illusion. In addition to the linear (degree=1) redirection function used in previous works, we consider second-degree polynomial functions. This gives us better control of the offset between the virtual and physical hand and ultimately of the hand trajectory when reaching the target.

We then carry out a user study. We compare 6 new redirection functions to the one used in the literature. The results show that these new redirection functions do not deteriorate the illusion while offering more flexibility to designers. Indeed, our results suggest that designers can manipulate the trajectory of the real hand and thus avoid potential collisions with physical objects or even with robots [16, 23].

2 RELATED WORK
We first discuss the visuo-haptic illusions, on which the Hand Redirection technique is based. We then describe precisely how hand redirection is implemented and evaluated in the literature.

2.1 Visuo-haptic Illusions
Visuo-haptic illusions manipulate a user’s perception of their body and/or environment by creating a conflict between their sight and proprioception. These illusions are used to enhance realism, interaction space and/or multimodal feedback in VR [1, 8]. They are mainly based on visual dominance [15, 18]. When sight conflicts with a sense (in this case proprioception), it tends to be privileged to resolve the conflict [10, 11]. Several virtual reality interaction techniques exploit this visual dominance. For example, by reducing or increasing the translations and rotations of the user’s head, one can imperceptibly manipulate the sensation of walking in a straight line [29, 32, 33]. It is also possible to manipulate the visual representation of virtual objects or the user’s avatar, for example, to alter the perception of the weight of an object [9, 20, 30], its size [4] or the stiffness of a spring [25].
2.2 Hand Redirection

Hand redirection is a particular visuo-haptic illusion where the avatar of the user’s hand (virtual hand) is progressively displaced from the real hand during a movement [21]. Both hands (real and virtual ones) are no longer co-located which creates a specific mapping between a real and virtual surface or object. When this offset is not detected, the user relies on information from their vision (i.e. the position of their virtual hand) to estimate the position of their real hand. One of the main applications of this illusion is to use a single physical object as a proxy for several virtual objects [7, 19, 26]. For instance, a user can interact with three virtual cubes. However, there is only one physical cube needed in the real environment. During movement towards one of the virtual cubes, the user’s virtual hand is redirected so that the real hand always reaches the real cube [2]. This illusion can also be a tool for two-handed interaction [26] or active interface enhancement [1]. In the following section, we detail the implementation of this technique.

2.3 Usual Implementation

A common implementation of the hand redirection illusion is the Interpolated Reach [19]. They define the offset between the real hand and the virtual hand \( \Delta M \) with a linear function of the distance between the Real Hand \( \overrightarrow{P_RH} \) and the Real Target \( \overrightarrow{P_RT} \). The position of the Virtual Hand is then equation 1.

\[
\overrightarrow{P_V} = \overrightarrow{P_H} + \Delta M (\overrightarrow{P_RH}, \overrightarrow{P_RT})
\]  (1)

\[
\Delta M(\overrightarrow{P_RH}, \overrightarrow{P_RT}) = \left(1 - \frac{||\overrightarrow{P_RH} - \overrightarrow{P_RT}||}{||\overrightarrow{PO} - \overrightarrow{P_RT}||}\right) \lambda
\]  (2)

with \( PO \) the starting point which defines the area where the illusion is activated and \( \lambda = ||\overrightarrow{P_T} - \overrightarrow{P_R}|| \) the vector formed by the real and virtual targets. For ease of reading, we define the distance between the real hand and the target \( d = ||\overrightarrow{P_RH} - \overrightarrow{P_RT}|| \) and the distance between the starting point and the real target \( D = ||\overrightarrow{PO} - \overrightarrow{P_RT}|| \). Thus, equation 2 becomes

\[
\Delta M(d) = \left(1 - \frac{d}{D}\right) \lambda
\]  (3)

Note that \( D \) and \( \lambda \) are constant and as the real hand reaches the target, only \( d \) fluctuates. This equation is then a simple linear equation with two parameters \(-\frac{1}{D}, \lambda\). Equation 3 guarantees that when the real hand is on the starting position \( d = D \), the offset \( \Delta M \) is null and when the real hand reaches the real target \( d = 0 \),
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Figure 2: The hand redirection technique with a 2nd order polynomial function. On the left, the function \((L < 0)\) redirects the user faster at the start of the movement rather than at the end. Inversely, on the right, the function \((L > 0)\) redirects the user faster at the end of the movement rather than at the start. The offset curves \((\Delta M)\) are the same than those figure 8.

the offset equals \(\lambda\). In the case where the hand is further from the real target \((d > D)\), the offset is set to 0. This implementation can be seen on the left panel of figure 1. In an other implementation, the virtual hand position is set by rotating the virtual hand around the starting position using the angle formed by the real target, the starting position and the virtual target [24, 35]. This implementation can be seen on the right panel of figure 1. Both implementations are equivalent.

2.4 Detection Threshold

We evaluate and compare these techniques by estimating when a user detects an illusion: the maximum offset between the real and virtual targets for example. Typically, we determine when an illusion is correctly detected 75% of the time by varying a single illusion parameter like the redirection angle [35] (see figure 1-right). The parameter value found is called the detection threshold.

Different experimental protocols have been used to determine the detection threshold. The most common is the 2 Alternative Forced Choice (2AFC) [3, 12, 17, 24, 27, 35]: for each trial, the participant is exposed to the illusion for a given parameter value. At the end of the trial, the participant is asked to indicate in which direction their virtual hand is compared to their real hand. Hence, the participants make a binary choice (left or right). When repeated enough times it allows to determine the probability of detection of the illusion for each illusion parameter studied.

In summary, many implementations of hand redirection have been proposed and most of them rely on a linear redirection function. In this article, we generalize the equation 3 by considering polynomial functions of order greater than 1 (order 2). We then analyze the influence of these functions on the illusion detection threshold.

3 GENERALIZATION OF THE HAND REDIRECTION FUNCTION

Equation 3 is a first order polynomial: \(f_1(d) = (a \times d + b)\). We generalize this equation:

\[
\Delta M(d) = \begin{cases} 
  f_n(d)\lambda & \text{if } d < D \\
  0 & \text{otherwise} 
\end{cases}
\]

with \(f_n(d)\) a polynomial of degree \(n\) with two constraints: \(f_n(D) = 0\) and \(f_n(0) = 1\). These polynomials allow to create a large variety of redirection behaviour like redirecting faster at the start or the end of the movement. The polynomial function is then

\[
f_n(d) = \sum_{i=0}^{n} a_id^i
\]

with \(a_i\) the \(i^{th}\) coefficient to be determined. When \(n = 1\) (see equation 3), there is no degree of freedom, we have \(a_1 = -\frac{1}{D}\) and \(a_0 = 1\) because of the continuity constraints at the target and the starting position. With \(n > 1\), the function has 1 or more degrees of freedom.

In this article, we focus on second-order polynomials and their influence on the detection threshold of the hand redirection illusion. In this case, equation 4 becomes

\[
\Delta M(d) = f_2(d)\lambda = (a_2d^2 + a_1d + a_0)\lambda
\]

This equation has 1 degree of freedom because there are only 2 constraints for 3 parameters. Figure 2 shows two examples satisfying the constraints. We chose to write the equation with a Bézier Curve [13] to represent the degrees of freedom with control points that can easily be manipulated visually.
A Bézier Curve defines a polynomial of degree $n$ from $n + 1$ control points $(P_i)$:

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i}t^i P_i$$

with $n$ the order of the polynomial, $B_0(t) = D - d$ and $B_n(t) = ||\Delta_M||$ and $t$ the Bézier variable varying between 0 and 1. The first $(P_0)$ and last $(P_n)$ control points correspond respectively to the starting position and the virtual target position. The other control points allow to visually control the speed at which the redirection is applied as the user approaches the target.  

In this formalism, equation 3 is a Bézier curve with two control points $P_C0 = (D, 0)$ et $P_C1 = (0, 1)$. For a second-order polynomial, equation 7 becomes

$$B(t) = (1-t)^2P_{C0} + 2t(1-t)P_{C1} + t^2P_{C2}$$

where $P_{C1}$ is the control point representing our degree of freedom. Figure 3 illustrates 6 redirection functions by varying the position of the control point $P_{C1}$. We define each redirection function with a variable $L$. For $L < 0$, the virtual hand is redirected away from the real hand faster than with the linear function.

And the opposite is true for $L > 0$. Finally, for all functions, the virtual and real hands are at the same position when the real hand is at the starting point and offset by $||\Delta||$ when the real hand is at the targets.

In reality, because our input variable is $d$ and not $t$, it is necessary to solve this two equation system by determining $t$ according to $d$ and then computing the offset $B_{sl}(t)$.

### 4 USER STUDY

The aim of this user study is to evaluate the influence of non-linear redirection functions on the detection threshold of the hand redirection illusion. We focus on second-order polynomials illustrated in figure 3. The experimental protocol is similar to Lebrun et al. [24] and Zenner et al. [35] where participants realize a pointing task in VR. After each repetition, participants select a Two Alternative Forced Choice (2AFC) about the direction of redirection (Left or Right) as well as if they detected the illusion (Yes or No).

### 4.1 Participants and Apparatus

The study was conducted with 19 participants (9 male, 10 female), aged from 20 to 29 years old (23.8 average). All participants were students volunteer from Sorbonne University. Amongst them, 2 were left-handed, 1 ambidextrous, and 15 right-handed. All participants had normal or corrected to normal eyesight (5 participants wore glasses or contact lenses). 3 of them had a regular VR experience, 11 had previous VR experience and 3 had no experience at all. No participants had musculoskeletal or proprioception disorders.

This user experiment was approved by the ethics comity of Sorbonne Université n°2020-020.

Participants were seated in front of a table wearing a VR HMD (HTC Vive Pro) and a hand harness with a Vive Tracker attached to it (see Figure 4). The position and orientation of the hand and finger are tracked with a precision of 1mm and 0.3°. We choose the HTC Vive Pro because it was available and provide an appreciable comfort for the participants. However our experiment protocol could be reproduced with a more accessible VR HMD.

A blue haptic marker is placed on the table as a starting position. 4 targets are arranged in an arc of a circle 56cm away from the starting point and offset by 15° from each other. We choose this distance so that all participants could reach the targets while seated. Similarly, the angular offset is set greater than the largest angle offset and small enough that participants couldn’t detect it. Targets have a push-button on top for the users to press. Targets on the far right and far left are dummy and participants never interact with them. They are here to further “hide” the illusion from participants seeing the real setup before putting the HMD on.

The virtual scene illustrated in figure 4 is a copy of the real environment. It was created in the Unity3D editor. The hand is represented with a static hand with the index pointing forward. During a trial, only a single virtual target is shown to the user, the one they should point at.

### 4.2 Experimental Design

#### 4.2.1 Task and Stimulus

The experiment is a pointing task with a Two Alternative Forced Choice (2AFC) similar to Zenner et al’s experiment [35] which is the most common protocol for studying these illusions and allows to compare our results. The task starts with the user’s finger on the starting position, a virtual target then appears. The participant reaches the target, presses the physical button, and goes back to the starting position. We ask that participants move naturally and avoid sudden movements and do the entire movement in 4 seconds. Then, participants have to choose if they had detected the illusion or not and if their real hand was on
the left or on the right of their virtual hand. This first question is an
extension of the more typical protocol. In cases where participants
make a mistake with the largest amplitude of redirection (14° et
-14°), the ground becomes red to notify them. From preliminary
results and the state of the art [3, 35], participants should always
be able to correctly guess the redirection direction in this case. No
further information were given to participants.

4.2.2 Conditions. We control 3 independant variables. The first
variable is the Function of redirection L with 7 values: L =
−3, −2, −1, 0, 1, 2, 3 (see figure 3). Note that L = 0 is the linear refer-
ence function [19, 35].

The second variable is the Redirection Amplitude \( \theta \). It is the
angle formed by the real target, the starting position, and the virtual
target. We consider 9 values: -14°, -10°, -6°, -2°, 0°, 2°, 6°, 10°, 14°.
The extreme values should be easily detectable (14° and to some
extent, 10°) whereas the closest values to 0° should be very hard
to detect (2°). We compromised between having values covering
a large enough spectrum to have easily detectable values, enough
points to fit a psychometric curve on our data, and restricting the
experiment time per participant (<1h).

The last variable is the Physical Target, Left or Right Target,
introducing variability in the user’s gesture. The leftmost and right-
most physical targets are not used in the experiment.

4.2.3 Procedure. Participants are first informed about the objective
of the study and the task they need to perform. Careful attention
was brought on explaining the concept of hand redirection and how
to correctly answer the 2AFC: “Your virtual hand is represented in
the virtual scene. During the task, an offset is added gradually
between this virtual hand and your real hand. This offset shifts
the virtual hand either on the left or on the right of your real
hand.” Participants then put the hand harness and the HMD on.
Participants had time to accommodate with the illusion and the
virtual scene by doing 4 training trials where their real hand was
visible on top of their shifted virtual hand. The offset values were
-10°, -2°, 2° et 10°. After each trial, participants were informed of
the direction of redirection. They then realize the full experiment
without seeing their real hand position. At the end, they fill out a
demographic questionnaire.

4.2.4 Design. This study follows a within-subject design. Each
participant did 2 repetitions of each combination of the 9 Redi-
rection Amplitudes, 7 Redirection Functions and 2 Physical
Targets, i.e. 2 blocks of 126 trials. The different conditions are
pseudo-randomized in each bloc. In summary, the experimental de-
sign is 18 Participants × 2 blocks × 9 Redirection Amplitudes × 7
Redirection Functions × 2 Physical Targets = 4284 repetitions.

5 ANALYSIS
A typical analysis of this kind of experiment (2AFC) consists in
plotting the psychometric curve of the population to estimate the
detection threshold of the illusion.

5.1 Psychometric Curve
A psychometric curve (figure 6) consists in plotting the probability
of answering one choice of the 2AFC over a controlled parameter.
The resulting curve can be fitted with a sigmoid:

\[
P(X) = \frac{1}{1 + e^{-\frac{X-a}{b}}} \tag{9}
\]

where \(a\) and \(b\) are two parameters used to adjust the fit. \(X\) is
the controlled parameter and \(P(X)\) is the probability to answer one
of the two force choices. In our case, it’s the probability that the
participant chose Left over the Redirection Amplitude \(P(\theta = \theta)\).
Intuitively, \(P(\theta)\) closes in on 100% when the virtual hand is indeed
on the left of the real hand in higher amplitudes and inversely,
closes in on 0% when the virtual hand is on the right of the real
hand.

5.2 Point of Subjective Equality
The point of Subjective Equality PSE is where participants perceive
the real gesture as equal to the virtual one. Graphically, it is where
the curve crosses the 50% probability. Essentially, participants an-
swer randomly to the 2AFC. It is expected that this value is close
to a Redirection Amplitude of 0°.

5.3 Detection Threshold and Interval of
Non-Detection
The psychometric curve allows to determine detection thresholds by
looking for \(\theta\) so that \(P(\theta = IND_G) = 25\%\) and \(P(\theta = IND_D) = 75\%
[25, 35]. IND_G is the detection threshold when the virtual hand is
redirected on the left of the real hand and vice-versa for IND_D. We
use the reciprocal function of equation 9:

\[
X = -b \ln \left( \frac{1}{P(IND)} - 1 \right) + a \tag{10}
\]

The Interval of Non-Detection (IND) is then \(IND = IND_D - IND_G\). It represents the span of Redirection Amplitude where
participants don’t detect the hand redirection illusion.

The main aim of our analysis is to estimate if and how the IND
is influenced by the Redirection Function.
6 RESULTS

6.1 Outliers

We removed participants from the analysis when any of the following conditions were met:

- The left or right non-detection interval \(IND\) for the linear redirection function \(L = 0\) is less than -14° or greater than 14°, similar to [3].
- The correct response percentage is less than 80% for the 14° and -14° angles and for the linear redirection function \(L = 0\).

Therefore, 3 participants were excluded for a detection interval of 15.0°, 16.2° and 28.5° and one participant for a correct response rate of 60%. The results presented here are therefore those of the 15 remaining participants. The experimental design is therefore: 15 Participants \(\times 2\) blocks \(\times 9\) Redirection Amplitude \(\times 7\) Redirection Functions \(\times 2\) Physical Targets = 4032 repetitions.

6.2 Target effect

We calculated the non-detection interval \(IND\) for each of the two physical targets and each redirection function. A Two-Way ANOVA (Physical Targets \(\times\) Redirection Functions) on \(IND\) indicates no significant effect of Physical Targets \(\left(F_{1,15} = 0.003, p > 0.05\right)\), nor interaction effects \(\left(F_{6,15} = 0.984, p > 0.05\right)\).

6.3 Redirection Function effect on Detection

A One-Way ANOVA (Redirection Function) for each Redirection Amplitude on the illusion detection question shows no significant effect on the detection.

6.4 Interval of Non-Detection

Figure 6 shows psychometric curve for each Redirection function. The vertical bars indicate the Left and Right Intervals of Non-Detection. They vary on the left from -7.75° to -3.45° and on the right from 3.99° to 6.79°. Non-detection interval in the linear case \(L = 0\) is \(IND = 10.6°\).

These values are comparable to the results of Zenner et al. in [35]. The distance between the source and the target is within the same magnitude and their results are very close with an \(IND = 8.19°\). The results reported by [27] and [3] show higher \(IND\) (respectively \(IND = 26.7°\) and \(IND = 44.6°\)). However, the distance between the origin and the real target is much smaller: around 20 cm for the first one, and variable value for the second one (around 24 cm \(\pm 7.5\) cm), against 56 cm in our study.

Figure 7 represents Intervals of Non-Detection according to the redirection functions \(L\). The area around the curve represents the 95% confidence interval calculated with the 1000-sample Bootstrap technique. The curve tends to be constant, which would indicate that the detection interval appears to be invariant to the redirection function. A One-Way ANOVA of the Redirection Function over the \(IND\) reveals no significant difference: \(F_{3,15} = 0.876, p > 0.05\). An equivalence test carried out on all pairs of \(L\) Redirection Function, the Two One-sided T-test (TOST), confirms the equivalence with the lower limit -3.5° and the upper limit +3.5° \((p < 0.05)\). Nevertheless, the TOST does not allow us to conclude on the equivalence of the \(IND\) with -2° and +2° bounds.

We therefore did not find any significant effect of the Redirection Function on the detection of the illusion.

6.5 Point of Subjective Equality

Figure 7 shows the \(PSE\) for the different redirection functions. For the linear case \(L = 0\), the \(PSE\) is \(-0.23°\). As for \(IND\), our value of \(PSE\) is similar to the results obtained by Zenner et al. [35], with a \(PSE = -0.28°\).

A Two-Way ANOVA (Physical Targets \(\times\) Redirection Function) on the \(PSE\) indicates no significant effect of Physical Targets \(\left(F_{1,15} = 3.491, p > 0.05\right)\) nor interaction effect \(\left(F_{6,15} = 1.895, p > 0.05\right)\).

Table 1 shows a summary of our results.

![Figure 5: The interval of non-detection \(IND\) for each redirection function and for each participant.](image1)

![Figure 6: The psychometric function for each redirection function according to the angle of redirection. Vertical lines show the interval of non-detection \(IND\) for a redirection on the right (25%) and on the left (75%).](image2)
We logged the positions of the hand over time to analyse the real
Table 1: Summary of our results: Interval of Non-Detection
(Figure 8-Right).

6.6 Participant Analysis

Figure 5 shows the non-detection interval for each user (one colour
per participant) depending on the redirection function. We do not
observe any particular pattern such as groups of behaviors.

7 HAND TRAJECTORY ANALYSIS

We logged the positions of the hand over time to analyse the real
hand trajectory when reaching for the target as a function of the
 redirection function. We first removed trajectories were the hand
tracking was not optimal (<5%) and then grouped trajectories for all
participants by amplitude of redirection and redirection function.

Figure 8 illustrate all the trajectories as a function of the function
of redirection for the redirection amplitude 14°. We observe that the
trajectory shape is influenced by the redirection function L: a strong
 redirection at the beginning of the movement (L<0) generates a
smooth reversed C shaped trajectory (Figure 8-Left). In contrast, a
strong redirection at the end of the movement (L>0) generates a
trajectory with a stronger correction at the end of the movement.
(Figure 8-Right).

<table>
<thead>
<tr>
<th>L</th>
<th>IND</th>
<th>PSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>L=3</td>
<td>11.41°</td>
<td>-0.89°</td>
</tr>
<tr>
<td>L=2</td>
<td>10.87°</td>
<td>-0.18°</td>
</tr>
<tr>
<td>L=1</td>
<td>9.97°</td>
<td>1.08°</td>
</tr>
<tr>
<td>L=0</td>
<td>9.89°</td>
<td>-0.23°</td>
</tr>
<tr>
<td>L=0 [35]</td>
<td>8.19°</td>
<td>-0.28°</td>
</tr>
<tr>
<td>L=1</td>
<td>10.26°</td>
<td>1.38°</td>
</tr>
<tr>
<td>L=2</td>
<td>9.37°</td>
<td>-0.13°</td>
</tr>
<tr>
<td>L=3</td>
<td>10.51°</td>
<td>-0.41°</td>
</tr>
</tbody>
</table>

Table 1: Summary of our results: Interval of Non-Detection
IND and Point of Subjective Equality PSE as a function of
the function of redirection L. Results in [35] are given for
comparison purpose.

8 DISCUSSION

This paper explores the design space of redirection functions for the
hand redirection technique: we generalized the current implement-
ation by considering polynomials of degree 2. The main objective
of the user study was then to investigate the influence of the redi-
rection functions on the interval of non-detection of the illusion.
We considered 6 redirection functions with different different dy-
namics (a shift at the beginning or at the end of the movement).
Our results show no significant effect of the redirection function
on the interval of non detection. Moreover, a Two-One Sided T-test
(TOST) suggests the equivalence of the non-detection intervals for
the different redirection functions.

We now discuss possible explanations why different redirection
functions do not affect the detection of the illusion. A two-
component model suggests that an aimed movement is divided
into two phases: first a ballistic movement followed by a correction
movement [34]. In the ballistic phase, the movement is faster as the
users do not rely on vision to correct errors. Recent studies [2, 14]
about visuo-haptic illusions show that some participants strongly
adjust their trajectory of their real hand towards the target only
during the final part of the movement. This observation is in line
with the two-component model suggesting that participants only
noticed the offset between the predicted and actual position of the
virtual hand at the end of the ballistic movement.

By generalising the redirection functions, we can choose whether
the offset between the real and the virtual hand mainly increases
during the ballistic phase or the correction phase. Indeed, with
L < 0, the offset is likely to increase during the ballistic phase
(beginning of the movement) while while L > 0, the offset is likely
to increase during the correction phase (end of the movement).
A difference regarding the detection of the illusion between L < 0
and L > 0 would suggest that users are more sensitive to the offset
increase in one of the two phases. In particular, we thought that
the amplitude of the offset at the end of the ballistic phase would
influence the detection of the illusion.
Figure 8: A visualization of participants trajectories for each redirection function evaluated. These trajectories come from all trials with a redirection amplitude of 14° on both physical targets.

Surprisingly, our results do not show differences regardless of the value of \( L \). One explanation could be that users are not sensitive to when the offset increases, but only to the maximum offset amplitude at the end of the trial, i.e. when the users touch the physical target. Another explanation might be that the ballistic phase is much shorter than expected. Participants’ movements could have been too slow due to our instructions favoring correction movements. Participants could also have focused too much on their virtual hand, rather than the target to accurately answer the 2AFC choice. As future work, we plan to study possible interaction effects between movement speed and redirection function. Indeed, faster movements and potentially more contrasted redirection functions could make some phenomena more salient. Future work should also control the effect of the distance from the real hand to the body as the visual and proprioceptive accuracy might vary in the ballistic (currently close to the body) and correction phase (far from the body). For instance, we will consider a reverse movement where the starting position of the hand is away from the body and the target is close to the body. Another possible explanation is that an effect is present but not visible due to the lack of data points. Future work should consider a larger number of participants and/or a larger number of samples per participant. The instructions might have been more difficult to interpret than expected as some participants might have noticed the visuo-haptic mismatch but were not able to correctly indicate the direction of the mismatch.

9 IMPLICATIONS FOR DESIGN
Our results have implications for design interactions. They suggest the designer can better control the real hand trajectory during the hand redirection. For example, in a complex scene with multiple physical objects that can be accidentally hit, the designer can use an appropriate function to avoid any obstacles along the real hand’s path. Also, many interaction techniques revolve around using actuated robots to provide haptic feedback. It is conceivable to alter the hand’s trajectory to avoid unwanted contact with the robot.

10 CONCLUSION
In this article, we generalized the redirection function of the hand redirection techniques by considering other redirection functions like 2nd order polynomials. We empirically compared the influence of 6 of those functions with the standard linear function. Our results suggest that the redirection function does not influence the Interval of Non-Detection. We also found that the redirection function offers more flexibility to designers to control the hand trajectory.

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