Target Expansion Lens:
It is Not the More Visual Feedback the Better!

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ABSTRACT

To enhance pointing tasks, target expansion techniques allocate larger activation areas to targets. We distinguish two basic elements of a target expansion technique: the expansion algorithm and the visual aid on the effective expanded targets. We present a systematic analysis of the relevance of the visual aid provided by (1) existing target expansion techniques and (2) Expansion Lens. The latter is a new continuous technique for acquiring targets. Expansion Lens namely, uses a round area centered on the cursor: the lens. The users can see in the lens the target expanded area boundaries that the lens is hovering over. Expansion Lens serves as a magic lens revealing the underlying expansion algorithm. The design rationale of Expansion Lens is based on a systematic analysis of the relevance of the visual aid according to the three goal-oriented phases of a pointing task namely the starting, transfer and validation phases. Expansion Lens optimizes (1) the transfer phase by providing a simple-shaped visual aid centered on the cursor, and (2) the validation phase regarding error rates, by displaying the target expanded area boundaries. The results of our controlled experiment comparing Expansion Lens with four existing target expansion techniques show that Expansion Lens highlights a good trade-off for performance by being the less-error prone technique and the second fastest technique. The experimental data for each phase of the pointing task also confirm our design approach based on the relevance of the visual aid according to the phase of the pointing task.

CCS Concepts

- **Human-centered computing~Graphical user interfaces**
- **Human-centered computing~Pointing**

Keywords

Pointing; Target Expansion; Visual Aid.

1. INTRODUCTION

To enhance pointing tasks, target expansion techniques (e.g. Bubble Cursor [5]) allocate larger activation areas to targets. These techniques act on the two parameters of Fitts' law (i.e. decreasing the movement amplitude A and increasing the target width W to W_X) to allow faster pointing movements [11]. However these techniques require empty space in the graphical interface. The system for which we study pointing techniques is an orthopaedic surgery system (i.e. Aesculap's OrthoPilot® Navigation System). Its graphical interface includes the required empty space, between the graphical elements [6].

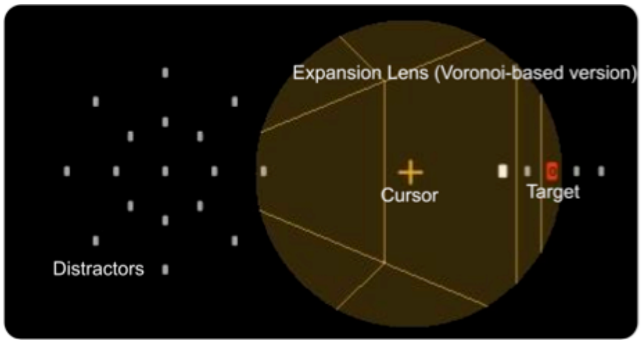

Figure 1. Expansion Lens: A yellow cursor-centered lens reveals the expansion algorithm (Voronoi cells). The current designated target is in white while the goal target is in red.

We distinguish two basic elements of a target expansion technique: the expansion algorithm and the visual aid.

First, the expansion algorithm distributes partly or wholly the free space among the targets. An example of space decomposition is the Voronoi tessellation that maximizes the use of empty space and is unambiguous since only one target is contained in each Voronoi cell. Several target expansion techniques implement a target expansion algorithm based on the Voronoi tessellation including Bubble Cursor [5] and VTE [6]. The expanded targets then correspond to the Voronoi cells and the user can point anywhere inside the target Voronoi cell instead of pointing at the target. In this paper the expansion algorithm we used for implementing the target expansion techniques is a Voronoi tessellation. But the techniques can be based on other expansion algorithms, provided that it is possible to compute the boundaries of the target expanded areas.

Second, the visual aid presents the resulting target expansion to the users. Previous studies demonstrated that the provided visual aid is key when using target expansion techniques [7]. Indeed, the users rely on the visual aid to take full advantage of the target expanded areas during the pointing tasks.

In this paper we investigate the visual aid provided by the target expansion techniques. The contributions of this work are twofold: (1) we put forward a systematic analysis of the relevance of the visual aid provided by a target expansion technique based on the three goal-oriented phases of a pointing task, and (2) we present a new target expansion technique Expansion Lens whose design is based on our analysis of visual aids. Expansion Lens uses a round area centered on the cursor: the lens (Figure 1). The users can see in the lens the target expanded area boundaries that the lens is

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hovering over. The key benefits of Expansion Lens are first to optimize the transfer phase of a pointing task by providing a simple-shaped visual aid centered on the cursor, and second to minimize error during the validation phase, by displaying the target expanded area boundaries.

After a review of related work, we present our analysis of the relevance of the visual aid provided to the user according to the three goal-oriented phases of a pointing task. This study serves as the basis for the design of Expansion Lens. We then report on a study that compares Expansion Lens with four target expansion techniques. They all use the same expansion algorithm but differ by the visual information provided to the users on the effective expanded targets.

2. RELATED WORK

We review previous work on performance of pointing movements and on visual information to be processed for movement production.

2.1 Performance of Pointing Movements

Fitts' law [4] predicts the time necessary to rapidly point to a target depending on the task's parameters. The law states that the pointing time T is a function of the movement amplitude A (the distance in order to reach the target's center) and the target's width W: $T = a + b \times \log_2(A/W + 1)$ eq. 1

where a and b are empirically determined constants which depend on the task's conditions. The logarithmic term in eq. 1 defines the task's Index of Difficulty (ID). The ID measures in bits the information transmitted by the user to the system when pointing at a target [19].

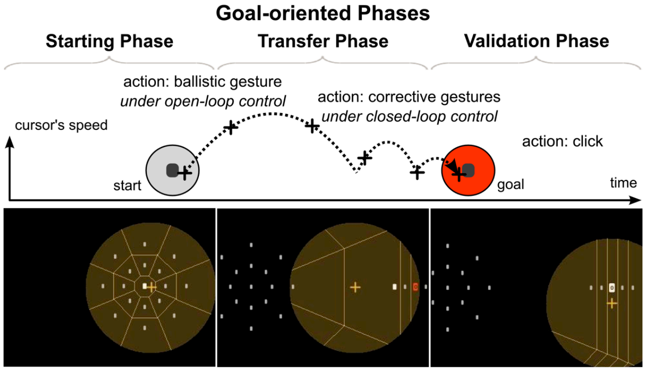

Figure 2. The three goal-oriented phases of a pointing task based on the Stochastic Optimized Sub-movement Model [12, 21]. Illustration of each phase with Expansion Lens.

Meyer et al.'s Stochastic Optimized Sub-movement Model [12, 21] describes the optimization process of the sub-movements that constitute a pointing movement. These sub-movements correspond to maxima in the cursor's velocity profile. The first one is called ballistic, while the following potential sub-movements are called corrective (Figure 2). Indeed, when the ballistic sub-movement does not stop on the target, a correction of the cursor position is necessary to reach the target.

The ballistic sub-movement is performed under open-loop control, which means that it is not updated with feedback information. However, it is optimized for the target's size that the users perceive before initiating the movement (starting phase in Figure 2). If the users estimate that the ballistic sub-movement is likely to stop on the displayed target area, they program it to be faster. Additionally, they program it in such a way that the two first sub-movements hit the target [12]. In the paper we call this effect the *ballistic gesture optimization effect*.

The impact of this optimization effect on performance is observable only with low-ID tasks. Indeed, this optimization effect is balanced by the subsequent corrective sub-movements when the task requires a high precision: "the use of more secondary sub-movements with increasing A/W allows the average total movement time to remain relatively short …" [12]. The term A/W determines the probability that a pointing movement contains corrective sub-movements.

When the ballistic sub-movement does not stop on the target, corrective sub-movements are necessary to reach the target. The end of the ballistic sub-movement and the consecutive corrective sub-movements are performed under closed-loop feedback control. This means that the users constantly update their movements according to what they perceive of the situation. The closed-loop feedback control thus describes the process allowing the users to benefit from the visual information provided by the target expansion technique during the pointing movement.

Finally, according to the Stochastic Optimized Sub-movement Model, the closed-loop feedback control of the corrective sub-movements allows the users to benefit from an expanding target even if this target expands unexpectedly and at the very end of a pointing movement. Consequently, with target expansion, Fitts' law models the pointing time if we consider the expanded target size (W_X) instead of the initial target size (W) [2, 3, 5, 11, 20, 23]. This has been shown to be reliable even when the aimed target is unpredictably expanded and the cursor has traveled 90 % of the distance to the target [3, 11, 23].

According to these models, the visual information provided by a target expansion technique is processed differently by the users depending on the type of sub-movements. The visual information thus has an impact on pointing performance: it is this impact that we analyze in a systematic way.

2.2 Processed Visual Information for the Control of Pointing Movements

As also stated by Meyer et al., the production of pointing movements (under open-loop and closed-loop control) requires certain information to be processed [12]. A first attempt to characterize the visual information provided by a target expansion technique is described by Guillon et al.: 3 axes characterize the visual aid provided by target expansion techniques [7].

First, the *dynamicity* axis characterizes the update rate of the visual aid as static, discrete or continuous. If the visual aid does not change during a movement, it is static. If the visual aid is dynamic, it can be discrete if the changes occur at discrete points in time and continuous if the changes occur with the gliding cursor movements.

Second, the *expansion observability* axis defines as explicit the techniques that display the target expanded area boundaries, i.e. the borders of the expanded areas defined by the expansion algorithm. In contrast, those which do not display the target expanded areas are defined as implicit.

Finally, the *augmented element* axis describes which element amongst the *cursor*, the *target* and the *space* is visually augmented to provide information to the users on the effective expanded targets.

The authors showed that explicit techniques are less error-prone than implicit ones, and that the pointing time increases according to the dynamicity: static techniques perform faster than discrete ones, which in turn perform faster than continuous techniques [7]. However, these axes cannot explain all the differences of performance. Indeed, previous studies [2, 20] reported performance differences for techniques described with the same values along the 3 axes. Examples of such techniques are provided in the following section.

2.3 Sample Target Expansion Techniques

Based on the above 3 axes [7], we present 8 existing target expansion techniques. We use 4 of them in the experimental study for assessing our new technique Expansion Lens. We first present 6 techniques that are based on a Voronoi tessellation for the expansion algorithm (see introduction section). We then present 2 versions of Implicit Fan-Cursor [20], which use an expansion algorithm allowing shorter – and thus faster – pointing movements than the algorithm based on a Voronoi tessellation.

VTE [6] is an (*explicit static space-based*) technique, since it statically displays the complete Voronoi diagram in the space between the targets. eVTE [7] is a VTE variant which defines the Voronoi diagram's transparency according to cursor speed in order to make the Voronoi diagram erasable on demand. The faster the cursor is, the more transparent the diagram is. eVTE is then an (*explicit continuous space-based*) technique.

Cell Painting [7], an (*explicit discrete target-based)* technique, displays only the Voronoi cell containing the cursor. TARGET [7], an (*implicit discrete target-based*) technique, enlarges the designated target but does not display the corresponding Voronoi cell's border, as opposed to VTE, eVTE and Cell Painting. The visual aid of Cell Painting and TARGET is updated only when the cursor enters a new Voronoi cell (i.e. *discrete* technique).

The existing cursor-based techniques are often continuous ones. Bubble Cursor's visual aid [5] consists of a cursor-centered bubble. During the movement, the bubble expands until it reaches (and if possible embraces) the closest target. The users continuously see which target is currently designated, i.e. which target they can select by clicking. Bubble Cursor [5] is therefore an (*implicit continuous cursor-based*) technique. Rope Cursor [7], another (*implicit continuous cursor-based*) technique, provides information using four lines. One thick line links the cursor to the closest target. Three thinner lines notify the proximity of neighboring targets to the users by growing in the corresponding directions of the targets.

The Implicit Fan-Cursor (IFC) expansion algorithm is not based on a Voronoi tessellation, since it dynamically modifies the target expanded area depending on cursor speed. Indeed, IFC designates a target only if the cursor approximately moves towards its direction. A basic version of IFC includes a single crosshair with an highlight of the designated target. Two visual aids have been studied for this technique: a circular-shape as with Bubble Cursor (*implicit continuous cursor-based*) and a fan-shape (*implicit continuous cursor-based*) which is a slice of the circular-shape oriented along the direction of the cursor's movement [20]. These two visual aids performed differently, while conveying the same target expansion and while being described by the same values along the 3 axes (*implicit continuous cursor-based*). This shows that the 3 axes while being a first attempt to characterize the visual aids is not sufficient to capture all the differences of performance. We extend this work by a systematic analysis of the visual information provided by a target expansion technique.

3. ANALYSIS OF VISUAL AIDS

Our analysis is dedicated to the visual information provided to the user during a pointing task. The analysis focuses on the relevance of the visual information provided by the technique and processed by the users. According to Norman's Action Theory [15, 22], the information processed by the users is related to their goals. But the user's goals vary according to the phase of the pointing task (Figure 2).

For presenting our analysis of visual aids, we first describe the information provided by the target expansion techniques. Therefore, we describe the visual sources of information and their meaning, i.e. the pieces of information. Second, we divide a pointing task into three goal-oriented phases. Third we categorize the information provided by the target expansion technique as primary or secondary, depending on their relative degree of utility for the goal-oriented decisions of each phase. We finally explain how primary and secondary information during each goal-oriented phase impacts on the performance.

3.1 Information Provided by Target Expansion Techniques

A graphical interface displays a cursor and a target. The pieces of information thus provided are the cursor's position, the target's position and the target's shape. The fact that the cursor is inside a target shape means that this target is designated. When we use a target expansion technique, a target can be designated without having the cursor on it. Therefore, a supplementary visual aid like a target highlight is necessary to inform the users that a target is designated.

A target expansion technique provides information about the target expanded areas or not, as described by the *expansion observability* axis in [7]. Cell Painting [7], an *explicit* technique, displays the designated target expanded area while TARGET [7], an *implicit* technique, displays an enlarged version of the target but not the target expanded area. Furthermore these two visual aids also highlight respectively a Voronoi cell and a target: this constitutes another piece of information.

In addition to the enlarged or expanded target shapes, a target expansion technique can provide other information. For instance we consider Bubble Cursor [5]. The bubble's position and circumference show the bubble's center and consequently the cursor's position. The bubble's radius shows the distance between the cursor and the closest target. The bubble's contact shows which target is designated. This information is sometimes completed by the bubble's resistance to contact, which shows the closest targets after the designated one. Finally, the bubble's border opposite the contact shows the distance to the next/previous Voronoi cell along the direction of the cursor's movement. This bubble's border moves at twice the cursor's speed: it can then be used to evaluate the distance to the next/previous target along the cursor's movement direction. This information enables the users to anticipate any contact of the bubble with a target.

We perform a similar analysis of the information provided by the 8 target expansion techniques described in section 2.3. This analysis is summarized in Table 1.

3.2 Relevance of Information according to Goal-oriented Phases

We classify the information as primary or secondary depending on the user's goals. Primary and secondary terms are used to distinguish between degrees of utility of information for achieving the current user's goal. We define three consecutive phases (Figure 2) that are based on the user's goals evolution: the *starting* phase, the *transfer* phase and the *validation* phase.

Table 1. Information analysis of 8 target expansion techniques. The information categorized as secondary during the transfer phase is typed in bold.

Visual Aid	Information Source	Information	Expansion Obser-vability	Primary for Starting Phase	Primary for Transfer Phase	Primary for Validation Phase
Bubble Cursor	Bubble Position	Cursor Position	Implicit	No	Yes	Yes
	Bubble Contact	Designated Target and Neighbors	Implicit	No	**No**	Yes
	Bubble Border Motion	Distance to Next Target	Implicit	No	**No**	Yes
	Bubble Radius	Distance to Designated Target	Implicit	No	**No**	Yes
IFC: Circular Shape	Bubble Position	Cursor Position	Implicit	No	Yes	Yes
	Bubble Radius	Distance to Designated Target	Implicit	No	**No**	Yes
IFC: Fan Shape	Fan Position	Cursor Position	Implicit	No	Yes	Yes
	Fan Radius	Distance to Designated Target	Implicit	No	**No**	Yes
	Fan Contact	Designated Target	Implicit	No	**No**	Yes
	Fan Spanning Angle	Cursor Speed	Implicit	No	**No**	Yes
	Fan Spanning Angle and Orientation	Potentially Designated Targets	Implicit	No	**No**	Yes
TARGET	Target Enlarged Shape	New Target Shape	Implicit	No	**No**	No
	Target Enlargement	Designated Target	Implicit	No	Yes	Yes
Cell Painting	Target Expanded Shape	Expanded Target Shape	Explicit	No	**No**	Yes
	Cell Highlight	Designated Target	Implicit	No	**No**	Yes
VTE	Goal Target Expanded Shape	Goal Target Expanded Shape	Explicit	Yes	Yes	Yes
	Distractor Expanded Shapes	Distractor Expanded Shapes	Explicit	No	**No**	No
eVTE	Goal Target Expanded Shape	Goal Target Expanded Shape	Explicit	Yes	Yes	Yes
	Distractor Expanded Shapes	Distractor Expanded Shapes	Explicit	No	**No**	No
	Diagram transparency	Cursor Speed	Implicit	No	**No**	Yes
Rope Cursor	Main Rope Cursor End	Cursor Position	Implicit	No	Yes	Yes
	Main Rope Target End and Mini-Ropes	Designated Target and Neighbors	Implicit	No	**No**	Yes
	1st Mini-Rope Motion	Distance to Next Target	Implicit	No	**No**	Yes
	Main Rope Length	Distance to Designated Target	Implicit	No	**No**	Yes

3.2.1 Starting Phase

The *starting* phase corresponds to the preliminary phase in Meyer et al.'s model [12]. The user's goal is to initiate the movement towards the target. The starting phase temporal interval is defined from the beginning of the task to the beginning of the ballistic sub-movement. The starting time thus describes the time needed (1) to understand that the task has begun, (2) to process the information related to the movement characteristics (direction, length, required accuracy), (3) to mentally program the movement and (4) to begin the cursor's motion.

The action resulting from the starting phase, i.e. the ballistic sub-movement, is produced under open-loop control. Consequently, during the starting phase the primary information is (1) the information that the task is started (a start signal or, for the case of sequential rapid selections, a feedback that the previous target selection is finished) and (2) the information used for preparing the movement [12] (the goal target's position, size and expanded size – we assume that the users have preliminary knowledge of the cursor's position before starting the task). All other information (e.g. all the expanded targets) is categorized as secondary for the starting phase.

The primary information is more likely to be processed by the users if we assume no preliminary knowledge of the goal target. In contrast, when selecting a known target (e.g. selecting the trash icon of a desktop) the users do not need to process this information. This is the case for the ISO 9241-9 standard [10] for evaluating pointing techniques: the information is known because the goal target's position sequence is repeated across the conditions.

With no preliminary knowledge of the goal target, since the users need time to process information [8, 9, 17], **the starting time increases with the primary information**.

3.2.2 Transfer Phase

The second phase is the *transfer* phase. The user's goal is to monitor the movement in order to bring the cursor into the goal target expanded area. This phase therefore comprises the cursor's movement from the beginning of the ballistic sub-movement to the last entrance of the cursor into the goal target expanded area – the cursor can cross the desired area while still being in the transfer phase for the case of overshoot. The transfer phase then includes the ballistic sub-movement and potential corrective sub-movements operated under closed-loop feedback control (Figure 2).

The primary information during this phase is the one necessary to achieve the user's goal, i.e. the one used as feedback to monitor the cursor's movement until its entrance into the goal target expanded area. The primary information includes the cursor's position, the goal target's features (position, size or expanded size) [12] and a target highlight mechanism. We classify as secondary other information (e.g. the proximity to targets) provided by the technique.

Because of the closed-loop feedback control of the corrective sub-movements, the primary and secondary information provided by the techniques impact on the transfer performance. **The secondary information slows down the transfer phase** because the closed-loop feedback control (1) processes the provided information and (2) identifies the primary information from the secondary information. As the transfer phase is likely to be the longest goal-oriented phase, we explain most of the performance differences observed between target expansion techniques [2, 6, 7, 20] by the impact of the secondary information on the transfer time: It is hence Not the More Visual Feedback the Better!

3.2.3 Validation Phase

The third phase is the *validation* phase. The user's goal is to correctly validate the selection. The phase starts when the cursor is set to the correct position to perform the selection (i.e. in the goal target expanded area), and ends when the selection is validated (e.g. a click). The errors occur in this phase when the users make incorrect validations.

During this phase, the users need information to ensure that a validation action will successfully achieve the selection task. Cognitively, they search for two certitudes: (1) that the cursor is in the expanded area of the goal target and (2) that the cursor is sufficiently far from the expanded area borders, since the cursor can slightly move during the validation action [1]. The primary information thus includes: the cursor's position, the proximity to neighboring target expanded areas and the goal target expanded area. The study by Guillon et al. [7] revealed that explicit techniques that display the goal target expanded area are less error-prone than implicit ones. The information concerning the other targets is secondary for this phase.

As for the starting phase, the users need time to process information. Therefore **the validation time increases with the primary information provided to the user but error rate decreases**. This reveals a speed/accuracy trade-off in the validation phase, although this phase is not modeled by Fitts' law. Indeed, while explicit information (i.e. displaying the goal target expanded area) is primary and limits errors [7], such information also increases the time of the validation phase.

3.2.4 Analysis: Complementarity and Limitation

By considering three goal-oriented phases, the analysis of visual aids extends (1) the *expansion observability* axis of Guillon et al. [7]; (2) adopts a complementary point of view on a pointing movement as compared to the kinematic one of Meyer et al. [12] Nieuwenhuisen et al. [14] and Plamondon et al. [16]. The analysis is based on the degree of relevance of visual information (i.e. primary or secondary information). During a phase, the relevance of visual information depends on the user's goals as well as on the closed-loop and open-loop control of the movements.

As a first step, the model assumes that the goal-oriented phases are independent and in sequence (no anticipation or parallelism between phases). This is an identified limitation of the analysis for further work. In particular the analysis does not incorporate the *ballistic gesture optimization effect* observable only with low-ID tasks (see related work). Indeed the information about the expanded target will slow down the starting phase but will enable us to optimize the transfer phase. The analysis does not consider this link between the two phases.

Finally, in our analysis we only considered techniques that provide the same visual aid for the three phases. The study by Guillon et al. has shown a high cost of switching between visual aids [7]. Extending the analysis to techniques combining different visual aids will lead us to consider this switching cost, which deserves further investigation.

4. Expansion Lens: Design

Based on the above analysis together with the 3 axes of Guillon et al. [7], we design a new target expansion technique: Expansion Lens (Figure 1). Two requirements guided its design:

- To optimize the transfer phase, we chose a simple-shaped visual aid centered on the cursor, thus minimizing secondary information for this phase;
- To optimize the validation phase regarding error rates, we chose an explicit visual aid.

Table 2. Information provided by Expansion Lens (in the same format than Table 1 for comparison)

Visual Aid	Information Source	Information	Expansion Observability	Primary for Starting Phase	Primary for Transfer Phase	Primary for Validation Phase
Expansion Lens	Lens Position	Cursor Position	Implicit	No	Yes	Yes
	Lens Content	Expanded Areas	Explicit	No	**No**	Yes

The information provided by Expansion Lens per phase is summarized in Table 2. Expansion Lens uses a round area centered on the cursor: the lens. The users can see in the lens the target expanded area boundaries that the lens is hovering over (Figure 1). Expansion Lens serves as a magic lens revealing the underlying expansion algorithm. We color the lens area with a translucent color (Figure 1).

As stated above the design rationale was to allow fast pointing movements with low error rates. For fast pointing movements, even if *static* techniques may be faster than *continuous* ones [7], we wanted to avoid the visual overload of the graphical interfaces potentially caused by *static* techniques like VTE [6]. We thus choose a *continuous* visual aid. To limit errors, we choose an *explicit* visual aid that displays simultaneously the expanded area boundaries of several targets (at least under average target density conditions). We limit the information provided during the transfer phase to this *explicit* information. We furthermore choose a *cursor-based* technique since during the transfer phase the cursor position is the primary information. Expansion Lens is the first target expansion technique that is (*explicit continuous cursor-based*).

The expansion algorithm we used for implementing the Expansion Lens is a Voronoi tessellation (like VTE or Bubble Cursor) [6]. But Expansion Lens can be based on other expansion algorithms, provided that it is possible to compute the boundaries of the target expanded areas. Moreover, the same implicit mode-switching as DynaSpot [2] can be implemented if we want to preserve the pixel-based selection. To do so we apply the DynaSpot size behavior to the lens transparency: the lens is invisible at low speed, it becomes visible when the cursor moves and it progressively returns to full transparency after the cursor stops moving and a small delay, called lag time in DynaSpot [2].

We conducted a pilot study with 10 participants to choose the best form factor for the lens. The results indicated that the participants preferred a round lens (8 participants out of 10) to a square one, with an intermediate lens size (a diameter between 100 and 300 pixels). The round form was significantly faster than the square form. We think that the round form reinforces the lens metaphor. The round form of the lens was the solution used in the experiment below.

5. EXPERIMENTAL STUDY

The goal of the experiment is to evaluate Expansion Lens in the light of our analysis of visual aids. To do so we conducted an experiment involving five techniques all based on a Voronoi tessellation: Expansion Lens, Cell Painting [7], TARGET [7], VTE [6], and Bubble Cursor [5]. As depicted in Tables 1&2, Expansion Lens, Cell Painting and VTE are explicit techniques while TARGET and Bubble Cursor are implicit techniques. The experimental study of Guillon et al. [7] showed that the explicit techniques are less error-prone than the implicit ones when performing low-ID tasks at a distance. In this experiment, we evaluate if this result is reliable when performing high-ID tasks with a desktop setting. Furthermore the selected compared techniques correspond to different values in our analysis of visual aids for the three goal-oriented phases (Tables 1&2). The two hypotheses H1 and H2 are related to the design rationale of Expansion Lens based on our analysis of visual aids.

- H1: For the transfer phase, Expansion Lens will be faster than the other techniques.
- H2: Expansion Lens being an explicit technique will result in fewer errors than implicit techniques will.

5.1 Implemented Techniques

The Expansion Lens had a diameter of 200 pixels. Cell Painting highlighted a Voronoi cell with a semi-transparent color. TARGET, VTE and Bubble Cursor were implemented as in [7].

5.2 Participants and Apparatus

Twenty volunteers (8 women and 12 men), ranging from 22 to 49 years (mean age is 28.8) participated in the study. 19 of them were right-handed. The experiment was conducted on a MSI GT60 laptop with a 2.3 GHz Quad-Core CPU, installed with MS Windows 7 and the default mouse configuration. The display size was 15.6” Full HD (1920×1080 pixels). We used a Razer Abyssus 2014 mouse. The test program was written in Qt/C++.

5.3 Task and Procedure

The study of the starting phase implies that the users do not know where the target is. As opposed to several previous studies [2, 5, 6, 7, 20] and in order to force the participants to look at the goal target, we modified the ISO 9241-9 [10] pointing tasks as follows. Eight goal targets were regularly distributed along a circle. A start target was at the circle center. The participants had to select the start target before selecting any goal target. The order of the eight goal targets of each condition was randomized. Thus, the participants had to identify the target before starting the pointing movement.

The targets and the distractor targets were visually similar: 8 pixels high and 4 pixels wide gray rectangles on a black background (Figure 1). The currently designated target was highlighted in white and the target to be selected whether it be the start target or a goal target was red, 1.5 larger than the distractors and contained a black zero (Figure 1).

The participants were instructed to go as fast as possible and to limit the errors at one incorrect trial amongst 25 to conform to a nominal 4% error rate. They had to select the right goal target to start the next trial. They used the 5 techniques one after another. The technique order was counterbalanced using a Latin square across participants. They started each technique with one training block (8 goal targets). After each technique, they completed an unweighted NASA-TLX [13] survey. Finally, they were asked to rank the 5 techniques in preference order, having a visual summary of the techniques on paper. The experiment lasted approximately 45 minutes.

5.4 Design

The experiment used a 5 techniques (*TECH: Expansion Lens, Cell Painting, TARGET, VTE and Bubble Cursor*) × (2 × 2 × 3) target layouts within-participant design.

The target layouts are defined by the following three factors (1) two movement amplitudes A: 252 and 504 pixels; (2) two Voronoi cell widths W_X: 8 and 16 pixels; (3) three distractor densities D: 0, 1 and 2.Thus the pointing task IDs were 4.06, 5 and 6 bits. We used Guillon et al.'s target layout [7] with different parameters. Increasing the distractor density D implied adding 3 distractors along the cursor's path, 2 being before the goal target circle and 1 after the goal target circle (on Figure 1, $D = 1$). We therefore obtained 12 (2×2×3) target layouts randomly ordered for each participant and for each technique.

96 target selections (12 layouts x 8 selections) per technique and per participant were recorded. A total of 9600 (96 target selections × 5 techniques × 20 participants) selections were recorded.

5.5 Movement Analysis

We detected the goal-oriented phases of each trial as follows: the starting phase ended when the cursor left the starting Voronoi cell, which was 32 pixels wide in all 8 directions; the transfer phase ended when the cursor entered the goal Voronoi cell for the last time; the validation phase ended when the goal target was selected.

For detecting the sub-movements, we first averaged 5 consecutive values of instant speed. We smoothed the averaged speed using a Gaussian kernel filter ($\sigma = 2$). In the resulting smoothed speed profile, we considered local minima as sub-movement beginnings.

5.6 Results and Discussion

In this section we present the results and discuss them in the light of our model of analysis of visual aids.

We removed 117 outliers (1.23 % of the data) due to double clicks or technical problems. Incorrect trials were removed from selection time measures. One-way Repeated-Measures ANOVA revealed a significant effect of techniques on selection time (F4,9496 = 23.8 ***). For comparing time, sub-movement numbers and NASA-TLX responses between techniques, we ran pairwise t tests using the Holm-Bonferroni method. For error rate, we performed a Pearson’s Chi-squared independence test between success of target selection and the 5 techniques. We compared preference rankings using pairwise Wilcoxon tests.

In Figures 3 to 5, the results are ordered in increasing order from the left to the right. We use the following code for test significance: ns denotes $p > .05$; * denotes $p < .05$; ** denotes $p < .01$; *** denotes $p < .0001$.

5.6.1 Starting Phase

Only VTE provides primary information (Table 1) during the starting phase: its starting phase is longer than the starting phase of all the other techniques (*** with all). For all the other techniques no significant time difference is observable. Without validating our analysis since only one technique provides primary information during the starting phase, these results fully support our analysis: *the starting time increases with the primary information* (section 3.2.1).

5.6.2 Transfer Phase

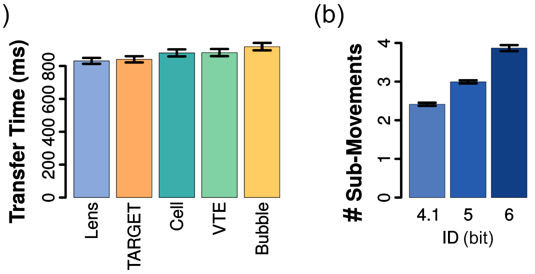

Figure 3: (a) Transfer time per technique, (b) number of sub-movements per task-ID.

As shown in Figure 3a Expansion Lens and TARGET are the best performing techniques, significantly faster than the other techniques for the transfer phase. The time differences are not significant between Expansion Lens and TARGET as well as between Cell Painting and VTE. All the other time differences are significant. These results confirm H1.

The results also support our analysis: *The secondary information slows down the transfer phase* (section 3.2.2). For instance, referring to Table 1 (value no in column “Primary for Transfer Time”), Bubble Cursor provides several pieces of information that are secondary during the transfer phase and is thus the slowest technique. There is one exception: the comparison of Cell Painting and VTE. Nevertheless the time difference between them is not significant. For an in-depth comparison we need to quantify the provided secondary information. This is part of our future work.

We finally note that VTE time performance is not as good as in the study by Guillon et al. [7] with lower-ID tasks. Indeed, most of the trials here included more than two sub-movements (Figure 3b). Consequently, the *ballistic gesture optimization effect* is compensated by several corrective sub-movements. The VTE time performance is thus determined only by the provided secondary information.

5.6.3 Validation Phase

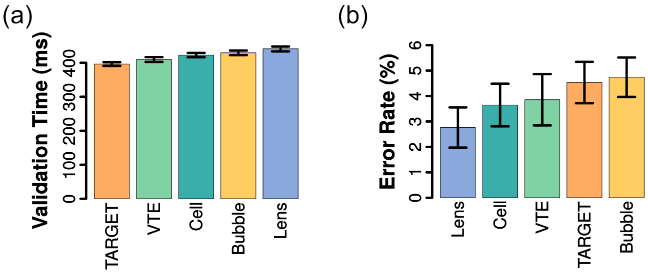

Figure 4: (a) Validation time per technique, (b) error rate per technique.

As expected the validation time performance per technique is different from the one of the transfer time. The validation time (Figure 4a) *increases with the primary information sources to be processed* (section 3.2.3), except for the comparison of Bubble Cursor and Expansion Lens. These results may suggest that the explicit information is longer to process than the implicit one. Indeed, Expansion Lens was slower than Bubble Cursor (ns) and VTE was slower than TARGET (ns).

The results also show that less sub-movements are initiated in the goal target cell with the explicit techniques than with the implicit ones, although the differences between the techniques are not always significant. This is an experimental evidence that seeing the goal target zone boundaries allows us to be more confident about the success of a potential click, and thus to save additional sub-movements.

Concerning the error rates, the results support H2 (Figure 4b): although differences were not all significant, the explicit techniques are all less error-prone than the implicit ones. Expansion Lens is less error-prone than TARGET (**) and Bubble (**). This confirms the previous result of Guillon et al. [7] for the case of higher-ID tasks.

5.6.4 Overall Results

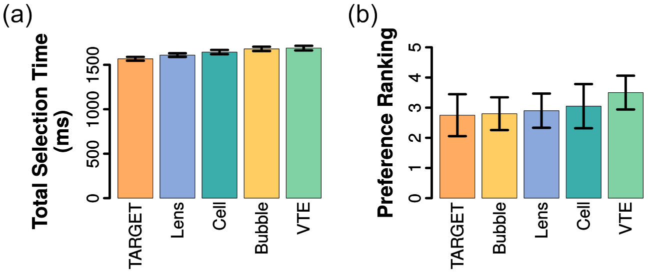

Figure 5: (a) Total selection time per technique and (b) preference ranking per technique (lower is better).

Overall Expansion Lens is the second fastest technique (Figure 5a) (*** with VTE, *** with Bubble Cursor, * with Cell Painting and ns with TARGET). Moreover, Expansion Lens is the less error-prone technique (Figure 4b) (** with Bubble and TARGET, ns with VTE and Cell Painting).

Figure 6 plots selection time as a function of ID and Table 3 gives the intercept, the slope and the adjusted R^2 for ID. All techniques fit the linear model with reasonable R^2 values.

The high slope value of VTE shows the decreased performance of this technique at high-ID. This confirms the *ballistic gesture optimization effect*. In the previous study by Guillon et al [7], low-ID tasks were considered and most of the pointing movements contained no corrective sub-movements. The *optimization effect* enabled VTE to perform significantly faster than all other techniques. In this experiment we considered high-ID tasks leading to several sub-movements (as explained in section 5.6.2). These sub-movements reduce the impact of the optimization effect and thus the performance of VTE strongly decreases with higher IDs (high slope value).

The slope values of TARGET and Expansion Lens, the two fastest techniques, are very close. The constant time difference between the two techniques can be explained by the time of the validation phase. As shown in Tables 1&2, Expansion Lens provides more primary information than TARGET. This increases the validation time but error rate decreases (Expansion Lens being less error-prone than TARGET (**)).

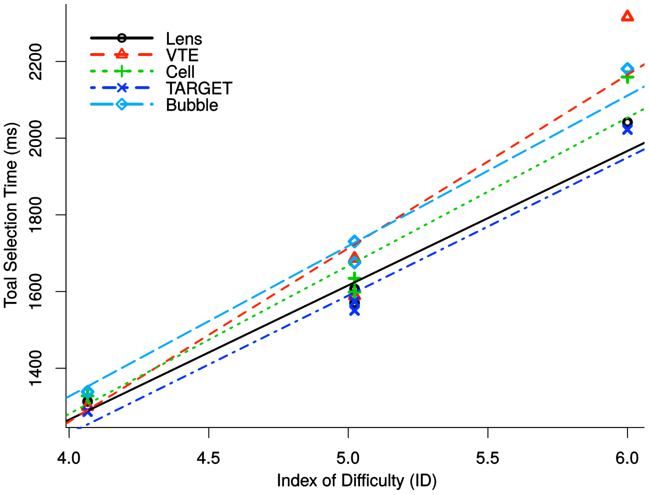

Figure 6: Total selection time per technique and ID.

Table 3: Linear fit: intercept, slope and adjusted R^2 using ID (effective width W_x)

Technique	T = a + b.ID		
	a *[ms]*	**b** *[ms/bit]*	**Adj. R²**
Expansion Lens	-135	350	0.94
TARGET	-209	360	0.95
Cell Painting	-263	386	0.93
Bubble Cursor	-242	392	0.96
VTE	-547	452	0.91

With regards to NASA-TLX criteria, Expansion Lens is rated the best technique on Mental Demand, Temporal Demand, Effort and Frustration. Moreover, Expansion Lens is rated the second best on Performance and Physical Demand. However these rating differences are not statistically significant. Finally we find no statistically significant difference between preference rankings. Within these narrow differences, TARGET is the preferred technique, followed by Bubble Cursor, Expansion Lens and Cell Painting. VTE receives the lowest preference ranking scores.

6. CONCLUSION

The key concept we put forward for the design of target expansion techniques is the relevance of the provided visual information according to the three goal-oriented phases of a pointing task. We analyzed several existing target expansion techniques in the light of the relevance of their provided information. This analytical framework also directs us to design the new Expansion Lens technique. The user study supports our analytical approach and the design rationale of Expansion Lens.

Our next step is to further study the impact on the performance of the primary and secondary information. The experimental results showed that the performance is impacted differently depending on the provided information that is processed by the user. This led us to quantify such information. The first approach we are currently exploring for quantifying information is to compute the Shannon entropy [18] of the visual stimuli provided to the user. For modeling the transfer phase, Meyer et al.'s law already takes into account the primary information because such information is necessary to perform the task. We suggest to add a third term to Meyer et al.'s law in order to model the negative impact of the provided secondary information on the performance: the transfer time will then be lengthened proportionally to the provided secondary information [8, 9, 17]. The key challenge is to take into account the high-level users' strategies in the quantification of the visual information processed by the user (i.e. the entropy calculation).

7. ACKNOWLEDGMENTS

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