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Research Article

What Kind of Grid Formations and Password Formats are Useful for Password Authentication with Eye-Gaze-Based Input?

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ABSTRACT

This study investigates which grid formations and password formats are useful for password authentication by means of eye-gaze-based input. Sixteen grid formations were made, in between 3×3 to 6×6 cells (columns-by-rows), for three password formats. The formats were an alphanumeric format, a pattern format, and a picture format. The participants were asked to memorize a 4-object or a 6-object password and register (Task 1), confirm (Task 2), and log in (Task 4) the password on each of the 16 grids with eye-gaze-based input. In Task 3, the participants evaluated each grid with a rating scale. The results showed that task-completion time was mostly shorter for the alphanumeric password format than for the pattern or picture format. Task-completion time of 4-object or 6-object passwords generally increased as the grid density increased, while the task-success rate at the first attempt decreased when the grid density increased. Task-completion time often was longer for grids with more rows than columns (vertical formations, e.g., 3×4 cells) than for grids with more columns than rows (horizontal formations, e.g., 4×3 cells). These results suggest that password authentication with eye-gaze-based input is best performed on horizontal grids with relatively few cells and a traditional (alphanumeric) format.

Keywords: Eye-gaze-based input; Eye tracking; Grid density; Grid formation; Password formats; Visual search

INTRODUCTION

In recent years, a variety of password systems have been proposed as alternatives to the traditional text-based systems that require manual input of alphanumeric characters. Generally, these password systems involve the use of non-alphanumeric, visual information [1]. For example, passwords can be made by drawing a figure on a grid, by indicating marker points on an image, or by selecting a sequence of symbols, patterns, or pictures from a display [2]. The latter type of password systems involves the recognition of visual information. Recognition is known to facilitate retention, and since humans have a vast memory for searching visual information, recognition-based passwords are often regarded as easier to memorize [3,4].

Authentication with these alternative password systems is commonly mediated by manual input. Recently, however, eye-tracking devices are also used, through which the user can use his/her gaze to click and point at visual objects on a display [5]. User authentication with eye-gaze-based input, or a combination of manual input and eye-gaze-based input, can be done in a variety of ways depending on the type of system. For example, the password system "EyePassShapes" [6] requires the user to draw strokes as a password by sequentially using eye tracking and a keyboard. In a system called "Cued Gaze-Points" [7], the user can select points on a sequence of images, while holding the spacebar on a keyboard for a few seconds to record his/her gaze. In both these password systems, compared with manual input only, the combination of a keyboard and eye-gaze-based input is potentially safer against "shoulder-surfing" in public spaces, i.e., password theft by a third party who observes and then copies a user's manual input of digits or text. The recognition-based password system "PassFaces" has even been tested with eye-gaze-based input only [8]. The authors reported that eye tracking would be a suitable and safe option for authentication, amongst others, on Automated Teller Machines (ATMs).

Besides alternative ways of information input for password systems, such as eye-gaze-based input, researchers have also been testing newer varieties of grid densities and formations for password input. As an alternative to the traditional 3×3 (+1) grid for digits, in particular grids with higher densities (more object keys) have been considered. For example, 3×4 and 4×4 grids (columns×rows) were used for the recognition-based system "Visual Identification Protocol" [2]. A 4×4 grid has been used for "ImagePass" [9], and a 5×5 grid for "Draw a Secret (DAS)" [10] and "Déjà Vu" [11]. Four equal numbered grid densities of 5×5, 6×6, 7×7, and even 10×10

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cells have been tested with DAS [12] and "Signature-based User Identification System (SUIS)" [13]. All these systems used manual input of relevant password information.

The grid is an important factor in password systems as it can hint to object position and identification [10,14]. The reason why the above-mentioned studies have explored the use of higher grid densities for password authentication is that a higher number of object keys (columns × rows) enables safer passwords. If a user has more object keys to choose from, he/she can form more complex passwords. In the systems "DAS" and "SUIS", increasing the grid density increased the password space [12,13], which is an indicator of security strength as specified by the total number of possible passwords (2^n, where n is the number of grid cells). Furthermore, in the case a user prefers relatively short passwords, a higher grid density lowers the chance that the correct sequence of object keys can be copied or discovered by third parties, for example, through shoulder-surfing. Research on the relation between grid density and password complexity, however, has shown mixed results. Research with a system that used manual input has shown that the use of grid densities of more than 4×4 cells had minimal influence overall on the complexity of passwords [15].

Together, research on password systems thus suggests that recognition-based systems are relatively easy to use because they help password retention, and that systems with a denser grid potentially allow safer password formation. Furthermore, it has been suggested that eye-gaze-based input could be suitable against password theft ("shoulder surfing"), especially in public spaces [8]. Given the necessity in today's world for an increasing variety of passwords on an increasing variety of (public or semi-public) devices with displays, the present study has two goals. First, we test which type of password format is suitable for password authentication with eye-gaze-based input. Second, we investigate what kind of grid formation is suitable for password authentication using eye-gaze-based input. So far, to our knowledge, no systematic, comparative research has been performed on these issues. In the experiment reported below, participants were asked to memorize a 4-object or 6-object password and register, confirm, and log in the password on an alphanumeric password format, a pattern format, and a picture format, on a wide range of grid formations, by using eye tracking. We obtained their task-completion time, their success rate, as well as preference data based on a rating scale, in order to test which password format(s) and grid formation(s) would be suitable for eye-gaze-based input.

METHOD

Three recognition-based password formats were used (Figure 1) The formats were an alphanumeric format, a pattern format, and a picture format, in which the participant was asked to identify and select a sequence of characters, dots, or icons, respectively, on the screen by using eye-gaze-based input. The formats were used with 16 grids ranging from 3×3 to 6×6 cells (columns × rows; see Figure 3 in the Stimuli section). For each format, the participant was asked to perform authentication tasks with a 4-object or 6-object password. Participants performed password registration (Task 1), password confirmation (Task 2), and password login (Task 4). This sequence of tasks is generally performed in any password system and mimics a real situation of password generation. For each of the 16 grid formations, the participant was also asked to judge how easily he/she could perform password input and could recognize a password when authenticating (Task 3, which was performed before password login, Task 4). A 7–point rating scale was used to obtain these judgments.

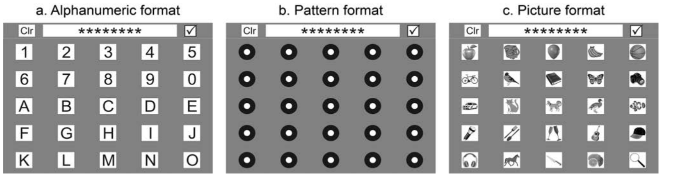

Figure 1: Examples of the three recognition-based password formats used in this study, on a 5×5 grid.

Participants

Seventeen participants (8 males, 9 females) with normal or corrected-to-normal vision participated. They were 21–44 years of age (*M*=27.12 years, *SD*=±5.95 years). The participant's height was in between 157 and 182 cm (M=167.82 cm, *SD*=±6.67 cm). Fourteen participants were Asian (Japanese, Chinese, and Indonesian), 1 participant was Caucasian, and 2 participants were Latino/Hispanic. The participants were paid for their participation. Data from two participants were not used for statistical analyses. One participant had difficulty employing the eye-tracking system, while the other had difficulty recalling and recognizing the passwords. After each participant had received an explanation and instructions about the experiment, he/she was asked to provide written informed consent as to his/her participation.

Apparatus

A monitor (Hewlett-Packard LP2065, 20-in, refresh rate 60 Hz) with a resolution of 1600×1200 pixels was used to present the experiment interface (Figure 2a). An eye-tracker device (Tobii EyeX©) was mounted on the lower edge of the monitor, at a height of 133 cm from the ground and at a viewing angle of 90°. The angles of the monitor and the eye-tracker were set at two viewing angles of 105° (90°+15°) and 120° (90°+30°). These angles were ideal for participants with a height in between 151-190 cm to register their eye gaze on the eye-tracking system [16]. In order to perform password authentication, the participant was standing in the middle in front of the monitor at a viewing distance of approximately 49 cm, as indicated by a floor mark. This viewing distance is close to the border of the operating distance of the eye-tracker device (for details, see [17]), and eye registration was unsuccessful when the participant was standing too close or too far away from the display [18]. The reason the participant performed the task while standing was to simulate a situation in which he/she would use eye tracking to register on an ATM-machine with a password.

Besides the monitor for the experiment interface, another monitor (Lenovo ThinkVision, 20-in, refresh rate 60 Hz) was used by the experimenter to control the order of password format, grid, and password length (Figure 2b). Both monitors were mounted on a monitor stand, opposite from each other. All experiment interfaces were programmed in Visual Studio C#(2015), and the data gathered from the participants were saved in a MySQL database. The experiment was performed under a room lighting condition at an illuminance of 122.35 ± 4.28 lux, as measured using a TOPCON Illuminance Spectro Meter IM-1000 at the location where the participant was standing. The display's luminance was measured using a TOPCON Luminance Meter BM-9. The measurements were performed ten minutes before the start of the experiment.

Figure 2: Impression of the experiment set-up. a. The participant was standing in front of the monitor which showed the experiment interface. b. The experimenter controlled the order of password format, grid, and password length for the participant using another monitor.

Stimuli

Sixteen different grid formations were made, ranging from 3×3 to 6×6 cells (columns-by-rows, Figure 3). They were set against a gray background (0.9 ± 0.03 cd/m^2) for the three password formats depicted in Figure 1. The first format was an alphanumeric password format (Figure 1a). For this format, alphanumeric characters, i.e., numbers and letters, were presented on a grid. In the case of a grid density of nine cells, i.e., a 3×3 grid, the digits 1, 2, 3, 4, 5, 6, 7, 8, and 9 were presented starting from the top left to the bottom right cell. If the grid density exceeded ten cells, letters (in alphabetical order) were added to the numbers. For example, on a 6×6 grid with 36 cells, the numbers 0 to 9, and the letters A to Z were presented starting from the top left to the bottom right cell. The alphanumeric characters in the grid cells were black with a luminance of 0.14 ± 0.01 cd/m^2, on a white background (2.42 ± 0.09 cd/m^2).

The second format was a pattern format (Figure 1b). The pattern format consisted of dots, which could be selected by the participant to create a shape or a pattern as a password. The dots were black (0.14 ± 0.01 cd/m^2) and white (2.40 ± 0.08 cd/m^2). A white dot with a radius of 47 pixels was placed in the middle of a black dot with a radius of 128 pixels, and both dots were presented together as a key. The third format was a picture format (Figure 1c), which consisted of icons in a fixed order on a grid, with the number of icons depending on the grid density. The icons were in gray-scale with a luminance range of 0.83 to 0.99 cd/m^2, against a white background (2.42 ± 0.11 cd/m^2). Each object key (i.e., alphanumeric character, dot, or icon) of a password was put in the middle of a grid cell with a size of 128 × 128 pixels, which was (4.16°×4.47°) in visual angle, and every pixel within an object key was (0.028°×0.030°) in visual angle.

The participant had four tasks (Procedure section below), for which two screen interfaces were made with a size of 1600 × 1200 pixels to perform password authentication. In Tasks 1, 2, and 4, the participant used his/her eye gaze to enter a password. For Tasks 1 and 2, the upper part of the screen (1600×125 pixels) consisted of two text boxes, a "Save" key, a "Confirm" key, and a "Clr" key. The "Save" key could be used by the participant to save a password.

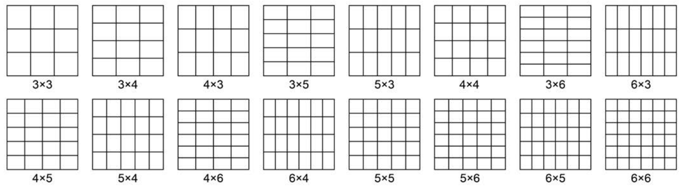

Figure 3: A schematic impression of the 16 different grid formations used in the experiment. Grid formations of 3×3 to 6×6 cells (columns×rows) were used. Note that the object keys (i.e., alphanumeric characters, dots, or icons) had the same size regardless of the number of grid cells.

When gazing at the "Confirm" key, the participant could confirm password input, while the "Clr" was used to clear his/her registered or confirmed input. The main part of the screen (1600×1075 pixels) displayed the password formats and grids. For Task 4, the upper screen of the task interface (1600×125 pixels) displayed a text box, a "Login" key, and a "Clr" key. The "Login" key could be used by the participant to authenticate his/her password into the system, while the "Clr" was used to clear this. Also in Task 4, the password formats and grids were displayed on the main part of the screen (1600×1075 pixels). When the participant selected an object key on the grid on the main part of the screen, an asterisk would be displayed on the text box at the upper part of the screen, and a chime sound would be played (1538 ms; 65-3733 Hz) to indicate that a selection was made. All (object) keys on the upper or main part of the screens could be triggered by eye gaze with a dwell time of 500 ms.

PROCEDURE

The participant was asked to stand in the middle in front of the monitor without crossing a floor mark. While standing, he/she was asked to relax, take a natural viewing position, and make no head movements during the experiment. Following this, the participant was shown a password on the screen, randomly generated for each of the three password formats, consisting either of 4 or 6 objects. He/she was then asked to memorize the password within a minute for a 4-object password and within two minutes for a 6-object password. After memorizing, the participant was instructed to perform the four tasks as described below.

Task 1: Password registration

The participant was instructed to register the memorized password on the screen interface by using his/her eye gaze. The participant could select the appropriate object keys displayed on a grid that was randomly selected from the 16 different grid formations. The password consisted either of alphanumeric characters (alphanumeric format), dots (pattern format), or icons (picture format). After registration, the participant was instructed to select a "Save" key.

Task 2: Password confirmation

After saving the password, on the same screen, the participant was asked to confirm the password by re-selecting the same object keys on the same grid. Following this, the participant was instructed to select a "Confirm" key. In case the confirmation was incorrect, for example, due to incorrect memorization or incorrect selection of object keys, he/she could retry the confirmation up to five attempts. If the participant failed to confirm the password on the fifth attempt, he/she was instructed to register again (Task 1) using a different password for the same password format and grid.

Task 3: Grid evaluation

After confirming a password, the participant was asked to judge whether he/she considered the grid that was used in Task 1 and 2 as easy to use for password registration and confirmation. This judgment was made on a scale between 1 (not easy) and 7 (very easy). Next, the participant was instructed to evaluate whether the password (4 or 6 objects) was easy to remember. This was also done on a rating scale between 1 (not easy) and 7 (very easy). Since this task did not require eye-gaze-based input, the participant used a mouse to make the rating-scale judgments on the screen. The meaning of "easy to use" was defined as how fast (estimated time needed) and successful (the number of attempts) the participant was in registering and confirming the password. "Easy to remember" was described as how much effort the participant thought to be necessary to memorize and recall a password.

Task 4: Password login

In this task, the participant was asked to log in into the system with the password that he/she had registered and confirmed before. If the participant noticed an error during login, he/she could retry to enter the password up to five attempts. If the login failed at the fifth attempt, the participant was instructed to register again (Task 1), starting by memorizing a different password for the same password format and grid. After the participant had finished all tasks for each grid formation for the three formats, he/she was asked to fill in a final questionnaire about his/her experience in daily life with passwords in general. The participant was explicitly instructed not to reveal any password or password formation strategy that he/she used in daily life.

The experiment was performed with counterbalance in the order of the three password formats. That is, five participants first performed the tasks in the alphanumeric format, then in the pattern format, and finally in the picture format, for each of the 16 grids. Another five participants started with the pattern format, followed by the picture format, and ended with the alphanumeric format. The remaining five participants started with the picture format and ended with the pattern format. For each format, the order of password length (4 or 6 objects) was varied as well. The time needed and the number of attempts needed by the participant to perform Tasks 1, 2, and 4 were recorded by means of the computer program. During the experiment, the participant was not informed about this in order to ensure his/her natural attitude towards the tasks.

Before the start of the experiment, each participant needed to register his/her eyes and perform calibration with Tobii EyeX© software at one of the viewing angles. In order to get familiar with all tasks, a practice program was performed in which the participant practiced Tasks 1, 2, and 4 with a 4-object or a 6-object password, twice for each password format, on a grid randomly chosen from the 16 grids. In between Tasks 2 and 4, Task 3 was practiced as well. The experiment took about 6 hours, divided over 2-hour sessions for 3 days. The procedure was approved by the Ethical Committee of the Faculty of Design, Kyushu University, Japan.

RESULTS

In Tasks 1, 2, and 4, task-completion time and input success rate were obtained. In Task 3, preference data based on a rating scale for the password formats and grid formations were gathered. Data from 4320 trials (15 participants×16 grids×3 tasks×3 password formats×2 password lengths) were collected. In Tasks 1, 2 and 4, in which the participant entered the password using his/her eye gaze, 11% (458/4320) of the time measurements were disproportionally slow, i.e., they were outliers in a positive direction. Given the dwell time for eye tracking of 500 ms per object key, disproportionally fast times were not obtained. The Median Absolute Deviation$_n$ method (MAD_n) was used to remove outliers [19]. That is, data points that were 2.5 times the MAD_n above the median were removed recursively until no additional outliers were identified.

Task-completion time difference between password formats

The time needed by participants (n=15) to perform Tasks 1, 2, and 4 (see Procedure section) for 16 grids in three password formats was measured. From here on we will call this "task-completion time". Since the data were not normally distributed, as confirmed with a Shapiro-Wilk test, non-parametric Friedman tests were performed in order to see whether task-completion time for all 16 grid formations varied with the password format. If significant, pairwise comparisons with Bonferroni-correction on the alpha-level (0.05/3) were performed to see which pair(s) of password formats showed a significant difference. Figure 4 shows the differences in median task-completion time (s) between password formats with 4-object or 6-object passwords for all grids.

The statistical details (Table 1) regarding task-completion time are as follows. In Task 1 (password registration), task-completion time over grid density (*df*=2, n=16) differed between password formats

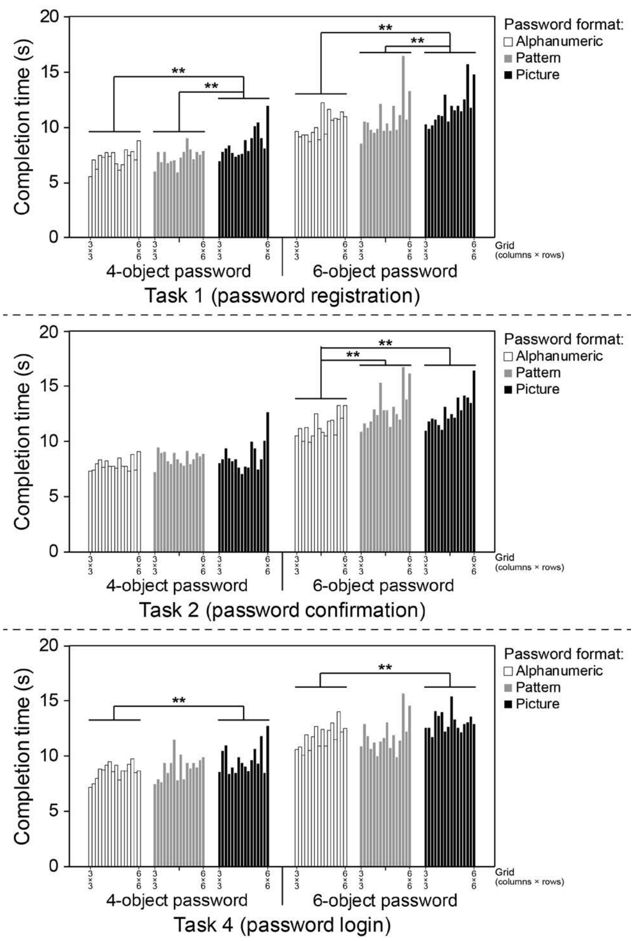

Figure 4: Median task-completion time (s) for alphanumeric, pattern, and picture password formats with 4-object or 6-object passwords for 16 grid formations in Task 1 (top), Task 2 (middle), and Task 4 (bottom). Asterisks show a significant difference in task-completion time between password formats (p<0.01).

Table 1: Pairwise comparisons of task-completion time between password formats for 4-object and 6-object passwords in Task 1, Task 2, and Task 4.

Password length	Pairs of password formats	Task 1	Task 2	Task 4
		Z	Z	Z
4-object passwords	AN - PA	-0.63	Task-completion time did not differ between formats, as confirmed by the Friedman-test.	-1.86
	AN > PI	**-3.31****		**-2.72****
	PA > PI	**-3.36****		-1.50
6-object passwords	AN>PA	-1.60	**-3.52*****	-0.55
	AN>PI	**-3.46****	**-3.52*****	**-2.95****
	PA>PI	**-3.05****	-0.47	-2.22

AN: Alphanumeric format, PA: Pattern format, PI: Picture format.

Task 1: password registration, Task 2: password confirmation, Task 4: password login.

Z: Wilcoxon signed rank test value.

>: faster task-completion time after bonferroni-correction

**p<0.01, ***p<0.001.

for both the 4-object (χ^2=14.00, p=0.001) and 6-object (χ^2=16.63, p<0.001) passwords. Follow-up pairwise comparisons revealed that the time to complete Task 1 with passwords in the alphanumeric format did not differ from task-completion time with passwords in the pattern format (4-object passwords: Z=-0.63, p=0.532; 6-object passwords: Z=-1.60, p=0.109). Completion time in the picture format, however, took significantly longer than in the alphanumeric format (4-object passwords: Z=-3.31, p=0.001; 6-object passwords: Z=-3.46, p=0.001) and the pattern format (4-object passwords: Z=-3.36, p=0.001; 6-object passwords: Z=-3.05, p=0.002).

For the data obtained in Task 2 (password confirmation), the Friedman test between password formats for 4-object passwords bordered on significance (χ^2=6.13, p=0.050) and for 6-object passwords was highly significant (χ^2=24.00, p<0.001). Pairwise comparisons for 6-object passwords revealed that the completion time for passwords in the pattern format did not differ from that for the picture format (Z =-0.47, p=0.642). However, completion time for alphanumeric passwords was significantly shorter than that for pattern passwords (Z =-3.52, p<0.001) and picture passwords (Z=-3.52, p<0.001). Completion time of Task 4 (password login) significantly differed between password formats for 4-object (χ^2=6.50, p=0.039) and 6-object (χ^2=7.88, p=0.019) passwords. The pairwise comparisons showed that completion time for passwords in the pattern format neither differed from that in the alphanumeric format (4-objects passwords: Z=-1.86, p=0.063; 6-objects passwords: Z=-0.52, p=0.605) nor from completion time in the picture format (4-objects passwords: Z=-1.50, p=0.134; 6-objects passwords: Z=-2.22, p=0.026, which was not significant with Bonferroni correction on the alpha level). Completion time for picture passwords, however, was significantly longer than that for alphanumeric passwords (4-objects passwords: Z=-2.72, p=0.007, 6-objects passwords: Z=-2.95, p=0.003).

The relation between task-completion time and grid density

In Tasks 1, 2 and 4, 16 data points for task-completion time were obtained for each of the three password formats. One data point was acquired for each square grid formation with a grid density of 9 (3×3), 16 (4×4), 25 (5×5), or 36 (6 ×6) cells. Two data points were obtained for the grids with an equal number of cells, yet each with a horizontal formation (more columns than rows) or a vertical formation (more rows than columns). Two data points were thus obtained for grids with 12 cells (3×4 and 4×3), 15 cells (3×5 and 5×3), 18 cells (3×6 and 6×3), 20 cells (4×5 and 5×4), 24 cells (4×6 and 6×4), and 30 cells (5×6 and 6×5). As shown in Figure 4, there was a general trend that participants took more time to input passwords in all three password formats when the grid density became higher. Pearson's correlation analyses were performed over the median of these 16 data points to examine the relation between task-completion time and grid density for 4-object and 6-object passwords in Tasks 1, 2, and 4. The r-values are shown in Figure 5. First, in general, the participants needed more time to complete 6-object passwords than 4-object passwords for all three formats in all tasks. Second, the results indeed clearly showed that task-completion time increased for denser grids, i.e., grids consisting of more object keys.

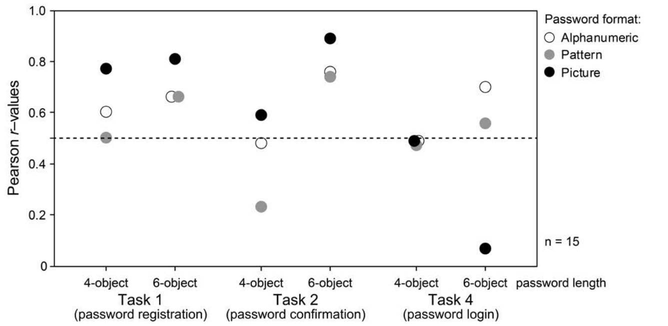

Figure 5: Pearson's correlation values between task-completion time and grid density. Task-completion time was obtained for eye-gaze-based input of 4-object and 6-object passwords in three password formats in Task 1, Task 2, and Task 4. The circles show Pearson r-values for the alphanumeric passwords (white), pattern passwords (gray), and picture passwords (black). All Pearson r-values higher than 0.50 (dashed line) show a significant positive correlation (p<0.05) between task-completion time and grid density.

The statistical details (Table 2a) are as follows. In Task 1 (password registration), for 4-object passwords, the median completion time ranged in between 5.58-11.96 seconds(s). Pearson's correlation analyses showed that the participants significantly required more completion time with increasing grid density. For the alphanumeric format (r=0.60, n=15, p=0.014) and the picture format (r=0.77, n=15, p<0.001) this correlation was significant. For the pattern format, the correlation bordered on significance (r=0.50, n=15, p=0.050). As the grid density increased, the participants also significantly needed more time for 6-object passwords, with

Table 2: (a) Correlations (Pearson *r*-values) between task-completion time and grid density in Task 1, Task 2, and Task 4, and (b) correlations (Pearson *r*-values) between the first-attempt-success rate and grid density in Task 2, and Task 4, for 4-object and 6-object passwords in three password formats.

a. Pearson r-values between the task-completion time and grid density

Task	4-object passwords			6-object passwords		
	AN	PA	PI	AN	PA	PI
1	**0.60***	0.50	**0.77****	**0.66****	**0.66****	**0.81*****
2	0.48	0.23	**0.59***	**0.76 ****	**0.74****	**0.89*****
4	0.50	0.47	0.49	**0.70****	**0.56***	0.07

b. Pearson r-values between the first-attempt-success rate and grid density

Task	4-object passwords			6-object passwords		
	AN	PA	PI	AN	PA	PI
2	**-0.67****	**-0.64****	-0.40	**-0.69****	**-0.76****	**-0.66****
4	-0.22	-0.33	**-0.70****	-0.23	**-0.66****	-0.40

AN: Alphanumeric format, PA: Pattern format, PI: Picture format.
Task 1: password registration, Task 2: password confirmation, Task 4: password login.
*p<0.05, **p<0.01, ***p<0.001.

the median completion time in between 8.55-16.44 s. For the alphanumeric format (r=0.66, n=15, p=0.005), the pattern format (r=0.66, n=15, p=0.005), and the picture format (r=0.81, n=15, p<0.001) this correlation was significant.

Similar to Task 1, the median completion time in Task 2 (password confirmation) increased when the number of grid cells increased. For 4-object passwords, it grew from 7.10 to 12.69 s. The correlation between task-completion time and grid density was significant for the picture format (r=0.59, n=15, p=0.016), but not for the pattern format (r=0.23, n=15, p 0.395) and the alphanumeric format (r=0.48, n=15, p=0.061), although the correlation for the latter bordered on significance. The median task-completion time for 6-object passwords ranged in between 9.97-16.86 s. The correlation between task-completion time and grid density was significant for the alphanumeric format (r=0.76, n=15, p<0.001), the pattern format (r=0.74, n=15, p<0.001), and the picture format (r=0.89, n=15, p<0.001).

Also in Task 4 (password login), there was a general tendency that participants needed more time to enter 4-object passwords when the number of grid cells increased (median completion time from 7.17-12.82 s). However, the correlations between task-completion time and grid density for the alphanumeric format (r=0.50, n=15, p =0.054), the pattern format (r=0.47, n=15, p=0.064), and the picture format (r=0.49, n=15, p=0.053) were not significant, yet bordered on significance. For 6-object passwords, the median task-completion time ranged from 10.00-15.77 s. There was a statistically significant correlation between task-completion time and grid density for the alphanumeric format (r=0.70, n=15, p=0.002) and the pattern format (r=0.56, n=15, p=0.024), but not for the picture format (r=0.07, n=15, p=0.798).

The relation between task-success rate and grid density

The password input success rate was measured based on whether the participant could perform Tasks 2 and 4 at the first attempt. For Tasks 2 and 4, data from 2880 trials in total were obtained (15 participants×16 grids×2 tasks×3 password formats×2 password lengths). Most of the trials (91%, 2627/2880) were completed at the first attempt with 4-object or 6-object passwords for all grids and password formats. We examined the correlation between task-

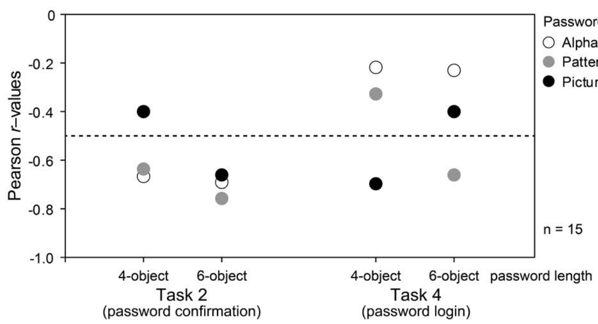

Figure 6: Pearson's correlation values between successful password input at the first attempt and grid density. The first-attempt-success rate was obtained for eye-gaze-based input of 4-object or 6-object passwords in three password formats in Task 2 and Task 4. The circles show Pearson *r*-values for alphanumeric passwords (white), pattern passwords (gray), and picture passwords (black). All Pearson *r*-values lower than -0.50 (dashed line) show a significant negative correlation (p<0.01).

success rate and grid density for these data. The results showed a negative correlation: when the grid became denser, the number of participants who successfully entered the password with eye-gaze-based input at the first attempt decreased. Figure 6 shows the Pearson *r*-values for the relation between first-attempt-success rate and grid density in Tasks 2 and 4 for the 4-object and 6-object passwords performed for the three password formats.

The statistical details (Table 2b) are as follows. In Task 2, the first-attempt-success rate with 4-object passwords decreased when the number of grid cells increased for all three formats. Although there was no statistically significant correlation between first-attempt-success rate and grid density for the picture format (r=-0.40, n=15, p=0.123), for the alphanumeric format (r=-0.67, n=15, p=0.005) and the pattern format (r=-0.64, n=15, p=0.007), this negative correlation was significant. For 6-object passwords, the first-attempt-success rate also significantly decreased as grid density increased for the alphanumeric format (r=-0.69, n=15, p=0.003), the pattern format (r=-0.76, n=15, p=0.001), and the picture format (r=-0.66, n=15, p=0.005). In Task 4, the first-attempt-success rate for 4-object passwords also significantly decreased when the number of grid cells increased in the picture format (r=-0.70, n=15, p=0.002), but not in the alphanumeric format (r=-0.22, n=15, p=0.420) and the pattern format (r=-0.33, n=15, p=0.219). For 6-object passwords,

Table 3: The differences in task-completion time (s) between horizontal and vertical grid configurations for 4-object and 6-object passwords in the three password formats in Task 1, Task 2, and Task 4.

Task	#Grid cells	Grid density (columns × rows)	Alphanumeric format						Pattern format						Picture format					
			4-object password			6-object password			4-object password			6-object password			4-object password			6-object password		
			N	Mean (SD)	Z	N	Mean (SD)	Z	N	Mean (SD)	Z	N	Mean (SD)	Z	N	Mean (SD)	Z	N	Mean (SD)	Z
1	12	3×4	12	6.45 (1.01)	-0.47	12	9.02 (1.85)	-0.47	13	7.17 (1.36)	-1.22	13	9.58 (2.19)	-0.59	12	6.93 (1.46)	-1.10	11	9.69 (1.18)	-0.27
		4×3		6.16 (0.82)			8.69 (1.27)			6.59 (1.40)			10.48 (2.80)			7.85 (1.46)			10.06 (1.21)	
	15	3×5	13	7.06 (0.89)	-0.31	12	9.47 (1.20)	-2.20*	15	7.47 (1.92)	-1.02	12	9.91 (3.17)	-0.47	13	8.63 (1.98)	-0.73	13	11.40 (3.43)	-0.25
		5×3		7.07 (1.92)			8.47 (1.00)			6.91 (1.44)			9.76 (1.85)			7.90 (1.94)			11.47 (2.74)	
	18	3×6	13	7.28 (0.87)	-0.18	12	9.36 (1.02)	-1.33	13	7.61 (2.86)	-1.85	13	12.07 (3.14)	-2.76**	11	7.30 (1.65)	-0.53	9	12.72 (2.86)	-2.55*
		6×3		7.44 (1.65)			8.95 (0.87)			6.16 (0.96)			9.00 (1.02)			7.37 (1.16)			10.12 (0.68)	
	20	4×5	10	6.35 (1.15)	-0.36	11	10.75 (2.03)	-2.13*	15	8.06 (2.83)	-0.80	14	10.02 (2.64)	-0.03	13	8.31 (2.07)	-0.59	12	10.58 (1.92)	-1.41
		5×4		6.60 (1.44)			9.24 (0.44)			7.43 (1.74)			9.82 (2.14)			7.91 (1.78)			11.98 (4.74)	
	24	4×6	13	6.90 (0.83)	-1.57	12	10.62 (1.61)	-0.71	14	8.89 (3.25	-1.10	14	11.78 (3.85)	-1.29	11	8.37 (1.60)	-0.27	12	10.49 (2.12)	-1.57
		6×4		8.10 (2.01)			10.13 (1.31)			7.94 (1.82)			10.42 (2.54)			8.58 (2.39)			11.03 (1.90)	
	30	5×6	12	7.87 (1.26)	-1.26	14	11.11 (2.52)	-0.03	14	7.51 (2.45)	-0.47	14	17.80 (5.46)	-2.73**	14	9.16 (2.55)	-0.47	13	14.77 (4.55)	-2.27*
		6×5		7.28 (1.77)			11.39 (3.43)			8.02 (2.92)			11.01 (3.97)			9.03 (2.68)			12.19 (3.65)	
2	12	3×4	10	6.99 (1.02)	-0.15	13	11.21 (1.98)	-1.64	14	9.24 (2.80)	-0.22	11	11.08 (3.45)	-0.62	13	8.05 (1.25)	-1.29	15	11.98 (3.16)	-0.57
		4×3		7.05 (1.43)			10.07 (1.43)			8.62 (2.52)			10.91 (2.21)			9.07 (2.07)			12.39 (3.33)	
	15	3×5	14	8.40 (1.55)	-0.85	12	10.95 (1.82)	-1.18	13	8.14 (2.07)	-0.87	13	11.47 (3.25)	-1.22	13	8.04 (1.65)	-0.38	11	11.62 (2.72)	-0.89
		5×3		7.78 (1.86)			10.26 (2.30)			8.17 (1.85)			13.10 (3.23)			8.46 (2.17)			11.24 (2.28)	
	18	3×6	12	7.53 (1.03)	-0.16	9	10.92 (1.82)	-0.77	12	10.59 (5.15)	-1.88	14	15.37 (5.38)	-2.48*	12	8.08 (2.18)	-1.73	14	14.59 (5.05)	-1.54
		6×3		7.54 (1.14)			10.02 (1.56)			7.88 (1.72)			12.31 (3.70)			6.84 (1.13)			12.46 (3.04)	
	20	4×5	10	7.22 (1.43)	-1.17	11	10.63 (2.35)	-0.27	10	7.20 (1.29)	-1.07	10	11.72 (4.10)	-0.26	14	8.26 (1.78)	-0.22	12	11.82 (1.79)	-0.86
		5×4		8.07 (1.77)			10.00 (1.52)			7.62 (1.42)			12.43 (4.15)			8.48 (2.12)			11.18 (2.58)	
	24	4×6	9	7.35 (1.12)	-1.13	13	11.56 (2.37)	-0.04	12	9.29 (2.87)	-0.86	13	12.57 (3.84)	-0.11	12	9.78 (3.06)	-0.16	11	13.92 (5.17)	-0.71
		6×4		7.67 (0.74)			11.83 (2.58)			8.45 (2.58)			12.52 (2.93)			9.75 (2.41)			11.64 (2.18)	
	30	5×6	15	10.12 (3.91)	-2.73**	12	13.02 (3.43)	-2.12*	10	8.68 (2.97)	-0.76	8	14.22 (3.48)	-2.38*	13	8.35 (1.80)	-1.22	14	13.63 (3.86)	-0.47
		6×5		8.21 (1.92)			11.01 (2.76)			7.82 (1.86)			10.52 (2.76)			9.51 (2.40)			13.43 (3.48)	

4	12	3×4	14	7.44 (1.45)	-1.10	11	10.58 (1.78)	-1.07	15	8.18 (2.27)	-1.19	13	12.54 (4.92)	-0.87	14	9.37 (2.61)	-0.79	13	12.45 (3.10)	-1.36
		4×3		8.27 (1.81)			9.67 (1.59)			8.90 (3.17)			11.40 (2.98)			10.10 (2.45)			11.44 (1.85)	
	15	3×5	10	8.18 (1.35)	-0.15	12	12.50 (3.03)	-2.67**	13	8.75 (2.04)	-0.25	14	11.84 (4.36)	-0.35	13	8.35 (1.16)	-0.66	11	11.91 (3.02)	-1.51
		5×3		8.91 (3.04)			9.92 (1.59)			8.54 (2.15)			11.33 (2.20)			8.84 (1.90)			12.74 (2.92)	
	18	3×6	12	8.74 (1.85)	-0.70	12	12.63 (3.84)	-1.88	10	10.61(3.26)	-2.70**	11	12.16 (4.90)	-0.36	13	10.12 (3.28)	-0.31	12	12.06 (2.06)	-0.55
		6×3		8.34 (2.09)			10.57 (1.89)			7.74 (1.66)			10.58 (2.01)			9.95 (3.42)			12.80 (4.04)	
	20	4×5	10	8.51 (3.24)	-0.87	11	11.80 (3.49)	-0.45	11	10.11(3.44)	-2.76**	13	13.51 (5.96)	-0.66	11	9.51 (2.48)	-0.98	12	15.53 (4.81)	-0.55
		5×4		7.71 (1.61)			10.60 (1.84)			7.65 (2.01)			11.34 (2.55)			8.42 (1.78)			15.43 (7.22)	
	24	4×6	11	8.70 (2.78)	-0.09	13	11.71 (2.41)	-0.80	10	8.16 (1.55)	-0.56	11	11.82 (4.43)	-1.25	13	9.64 (2.90)	-1.36	11	12.40 (3.13)	-1.25
		6×4		8.44 (1.36)			12.43 (3.70)			8.26 (1.64)			10.14 (2.27)			10.96 (3.18)			11.10 (2.27)	
	30	5×6	9	9.72 (2.70)	-1.72	12	12.00 (2.98)	-0.24	14	9.57 (3.42)	-0.09	10	13.40 (5.19)	-0.56	10	11.95 (6.10)	-2.29*	12	13.15 (4.06)	-0.78
		6×5		8.05 (1.51)			11.62 (2.51)			9.76 (3.54)			11.34 (2.63)			8.10 (1.49)			12.83 (2.41)	

Note: N: Number of participants, SD: Standard deviation, Z: Wilcoxon signed rank test value * p<0.05, ** p<0.01

first-attempt-success rate showed no significant correlation with grid density for the alphanumeric format (r=-0.23, n=15, p=0.392) and the picture format (r=-0.40, n=15, p=0.125). There was a statistically significant negative correlation, however, between first-attempt-success rate and grid density for the pattern format (r=-0.66, n=15, p=0.006).

Task-completion time difference between horizontal and vertical grid configuration

In cases of grids with an equal number of cells (i.e., an equal number of object keys), we also checked whether the formation of the grid influenced the task-completion time. Leaving the square grids aside, we directly compared task-completion time for grids with more columns than rows (e.g., columns×rows=4×3) against grids with more rows than columns (e.g., columns×rows=3×4). For each task, six pairs of grid formations were compared using data points with no outliers for each of the three password formats. We called grids with more columns than rows "horizontal" configurations, and grids with more rows than columns "vertical" configurations. Table 3 shows the differences in average task-completion time (s) between horizontal and vertical grid configurations for 4-object and 6-object passwords for the three password formats.

For the alphanumeric format in Task 1 (password registration), the average task-completion time for 4-object passwords was nearly similar between horizontal and vertical configurations of 12, 15, 18, 20, 24, and 30 cells (object keys). For the pattern and the picture formats, the time was also nearly similar between horizontal and vertical configurations in between 12-30 object keys. No statistically significant difference between horizontal and vertical pairs was found for any of the three password formats. For 6-object passwords, however, pairwise comparisons revealed six significant differences. The first two concerned the alphanumeric format, where vertical configurations of 3×5 and 4×5 (columns × rows) grids required a longer completion time than horizontal configurations of 5×3 and 5×4 grids (Z=-2.20, p=0.028 and Z=-2.13, p=0.033, respectively). The next two significant differences were found in the pattern format between vertical 3×6 and 5×6 grids and horizontal 6×3 and 6×5 grids (Z=-2.76, p=0.006 and Z=-2.73, p=0.006, respectively). In the picture format, significant differences occurred in the same grid comparisons, i.e., between vertical 3×6 and 5×6 grids and horizontal 6×3 and 6×5 grids (Z=-2.55, p=0.011 and Z=2.27, p=0.023, respectively).

Four significant differences between horizontal and vertical grid configurations with equal grid density were found in the completion time of Task 2 (password confirmation). First, the time to confirm a 4-object alphanumeric password was longer in the vertical 5×6 grid than in the horizontal 6×5 grid (Z=-2.73, p=0.006). A significant difference also appeared in the task-completion time of the 6-object alphanumeric password (Z=-2.12, p=0.034) between these grid configurations. In the pattern format, vertical configurations of 3×6 and 5×6 (columns × rows) grids required a longer task-completion time than horizontal configurations of 6×3 and 6×5 (columns × rows) grids (Z=-2.48, p= 0.013 and Z=-2.38, p=0.017, respectively). In Task 4 (password login), the eye-gaze-based input also required more time in vertical than in horizontal grid configurations, significantly in four cases. First, the time to complete a 4-object pattern password took longer in the vertical 3×6 grid than in the horizontal 6×3 grid (Z=-2.70, p=0.007). A significant difference was also found between the vertical 4×5 and the horizontal 5×4 configuration for 4-object pattern passwords (Z=-2.76, p=0.006).

The third significant difference was between the vertical 5×6 and the horizontal 6×5 configuration for 4-object picture passwords (Z=-2.29, p=0.022). The last significant difference concerned the alphanumeric format, for which completion time of a 6-object password differed between the vertical 3×5 and the horizontal 5×3 configuration (Z=-2.67, p=0.008).

Participant judgments

In Task 3, participant judgments were obtained about the grid densities and formations. The participants judged the usability of each grid based on how fast (time) and successful (first attempt) they could register and confirm a password with eye-gaze-based input. They were also asked to judge how well they could recall and recognize a password on each grid density. The participants made judgments on a 7-point rating scale (1: Not easy, 7: Very easy). Regarding "easy-to-use" judgments, the participants judged the grid as increasingly less easy to use when the number of object keys increased, either with a 4-object or a 6-object password, for all three password formats. Pearson's correlation analyses showed a statistically significant correlation between the participant judgments and grid density, with r-values ranging from -0.81 to -0.96 (n=15, p<0.001). Regarding "easy-to-remember" judgments, the participants judged the password as less easy to remember when the number of grid keys increased, for both 4-object and 6-object passwords in all three password formats. Pearson's correlation analyses showed a statistically significant correlation between the participant judgments and grid density, with r-values ranging from -0.61 to -0.96 (n=15, p<0.02).

DISCUSSION

In this experiment, participants were asked to memorize a 4-object and a 6-object password for three types of password formats and register (Task 1), confirm (Task 2), and log in (Task 4) the password on a grid by using eye-gaze-based input. The three recognition-based password formats were an alphanumeric format, a pattern format, and a picture format (Figure 1). Grid densities and formations were varied in 16 ways in between 3×3 and 6×6 object keys (Figure 3). Participants also provided preference data about the grid densities and formations (Task 3).

The first purpose of this study was to investigate which type of password format is suitable for password authentication using eye-gaze-based input. The results showed that for 16 grids, password input with 4-object or 6-object keys required more time in the picture and pattern formats than in the alphanumeric format. In the majority of cases, task-completion time in the alphanumeric format was significantly faster (Figure 4). Participants are most likely more familiar with passwords consisting of numbers and letters in daily life, and memorization of alphanumeric passwords by "chunking" (grouping) may have enabled faster recall [4]. In general, more frequently used items are easier to recall [20] and possibly in the present experiment the participants had not much time to adapt to using icons (picture format) or dots (pattern format). The preference for the alphanumeric format was also reflected in the questionnaire taken after the experiment, which showed that 12 participants (80%) thought that the alphanumeric password format would be potentially suitable to use with eye-gaze-based input. Only three participants (20%) thought that the picture format could be useful, while none considered the pattern format useful.

The second purpose of this study was to investigate what kind of grid formation is useful for password authentication using eye-gaze-based input. The results showed that the participants generally needed more time to complete password registration (Task 1), confirmation (Task 2), and login (Task 4) on denser grids with more object keys, either with a 4-object or a 6-object password, in the three password formats. The majority of the correlations (Pearson r-values) between task-completion time and grid density was significant (Figure 5). This result accords with a previous study about password authentication without eye-gaze-based input [21], which showed that participants needed more search time when the number of grid keys increased. Previous research on eye movements already had reported that participants needed less search time for sparse layouts than for dense layouts [22]. It is thus likely that the participants needed more time to search the necessary object keys to form the password as the total number of key options increased. Another possible explanation for the fact that participants needed more time to make the password on a denser grid is the increased chance of incorrect object key selection with eye tracking. Although each object key had the same size regardless of grid density, incorrect key selection might have happened because the distance between object keys narrowed, causing the participant to sometimes unintendedly gaze on an incorrect object key, for example when the screen appeared for the first time. The participant rating scale judgments also showed that they considered a grid as significantly more difficult to use with eye-gaze-based input when the grid became denser.

Another minor point of denser grids found here is that the number of successful password inputs at the first attempt, either for 4-object or 6-object passwords, decreased when the grid became denser. Over half of the correlations (Pearson r-values) between first-attempt-success rate and grid density was significant (Figure 6). As the number of grid keys increased, the participants thus tended to make more mistakes, i.e., they selected objects incorrectly and needed more attempts. One reason could be that they more often incorrectly gazed at the wrong object key due to the grid density, as described above. Another reason is that with increasing grid density, the passwords became more complex. The passwords used by the participants were randomly generated according to grid density. For example, a password on an alphanumeric 3×3 grid consisted only of digits, while a password on an alphanumeric 6×6 grid consisted of digits and letters. The combination of the latter might have been more difficult to remember. This result related to the participant judgments, which showed that passwords were judged as significantly less easy to recall and recognize when the grid became denser. Future research is necessary to clarify this issue further.

The last finding related to grid formation is that the time needed to enter a password with eye-gaze-based input was often longer for grids with more rows than columns (vertical configurations) than for grids with more columns than rows (horizontal configurations), under equal grid density. Direct paired comparisons of task-completion time between horizontal and vertical formations with an equal number of grid keys revealed 14 significantly different pairs. In all 14 cases, task-completion time was significantly faster in horizontal grids than in vertical grids (Table 3). This strongly suggests that entering a password with eye-gaze-based input is faster on horizontal grids with more columns than rows and that vertical grids with more rows than columns are less efficient for eye-gaze-based input. Studies on the visual search of objects or words have reported similar results. When searching for visual objects on a screen, the direction of the participants' eye movements may occur more frequently horizontally than vertically [23]. It has further been shown that fixation time in visual search of vertical word lists is longer than fixation time for horizontal word lists [24]. A horizontal search model was also preferred for searching a target word in a full-screen search field [25].

In future research, the above points need to be confirmed, and some issues in the present study, as mentioned by some participants, need to be remedied. One limitation is that the “Save”, “Clr”, and “Confirm” key at the upper part of the interface screen for Tasks 1 and 2 were relatively close together and that some gaze time needed to be spent on selecting the correct key for these actions. Nevertheless, this also indicates that when using eye tracking, password keys need to have a fair size, and too dense grids will not be able to accommodate that, unless very sophisticated and expensive eye-tracking systems are used. Another issue that requires investigation is dwell time. Here we used 500 ms to confirm gaze on a certain object key. It is worthwhile to investigate whether a shorter dwell time can be used since this would speed up the password input process with eye tracking.

CONCLUSION

The usability of grid formations and password formats was measured by task-completion time and the success rate of task completion at the first attempt. Taken together, the results suggest that the chance of performing quick and successful password authentication by eye-gaze-based input decreases with increasing grid density and decreases with vertical grid configurations (e.g., with more rows than columns, as in 3×4, 3×5, 3 6, 4×5, 4×6, or 5×6 grids). Furthermore, in many cases, the alphanumeric password format seemed most useful, in that password input required relatively less time and relatively few mistakes were made.

DECLARATION OF INTEREST

The authors declare that they have no competing interests.

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