Q-A: Towards the Solution of Usability-Security Tension in User Authentication

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Abstract—Users often choose passwords that are easy to remember but also easy to guess by attackers. Recent studies have revealed the vulnerability of textual passwords to shoulder surfing and keystroke loggers. It remains a critical challenge in password research to develop an authentication scheme that addresses these security issues, in addition to offering good memorability. Motivated by psychology research on humans’ cognitive strengths and weaknesses, we explore the potential of cognitive questions as a way to address the major challenges in user authentication. We design, implement, and evaluate Q-A, a novel cognitive-question-based password system that requires a user to enter the letter at a given position in her answer for each of six personal questions (e.g., “What is the name of your favorite childhood teacher?”). In this scheme, the user does not need to memorize new, artificial information as her authentication secret. Our scheme offers 28 bits of theoretical password space, which has been found sufficient to prevent online brute-force attacks. Q-A is also robust against shoulder surfing and keystroke loggers. We conducted a multi-session in-lab user study to evaluate the usability of Q-A; 100% of users were able to remember their Q-A password over the span of one week, although login times were high. We compared our scheme with random six character passwords and found that login success rate in Q-A was significantly higher. Based on our results, we suggest that Q-A would be most appropriate in contexts that demand high security and where logins occur infrequently (e.g., online bank accounts).

Index Terms—Usable security; user authentication; cognitive question

I. INTRODUCTION

Compared with the tremendous advancement of digital devices over the past few decades, passwords are a stubborn legacy technology that hangs on for want of something better. Recall-based user-chosen textual password is the most widely used authentication scheme on the Web, but it is fraught with security problems because of password reuse [1] and predictable patterns [2, 3] that make this scheme vulnerable to online guessing attacks [4, 5]. Password restriction policies are found to have limited impact on ensuring security and in some cases adversely affect password memorability [2, 6]. System-assigned random passwords provide higher security, but suffer from memorability problems [7]. Multiple variants [8, 11] have been proposed to improve memorability in this respect, yet none of these schemes has shown significant improvement for the examined usability metrics.

Users have cognitive limitations that define our potential for interaction with computers. Existing password systems fail to fully address these limitations, nor do they leverage humans’ cognitive strengths.

A. Motivation

The most prominent dilemma studied in the research on user authentication is the delicate balance between memorability and preventing successful guessing. Existing schemes rely on information specifically memorized for the purpose of authentication, such as the string of characters that make up a textual password. This means that the information is less memorable for users than information that users already know because it is meaningful for them. This in turn means that users tend to choose passwords that are easy to guess.

Beyond guessing resistance, however, other security concerns have been shown to be at least as important. Florencio et al. point out [12] that observation attacks, such as shoulder surfing (external observation attack) and keystroke loggers (internal observation attack [13]), appear to be the most prevalent attacks, in which strong passwords are just as susceptible to being stolen by an attacker as weak ones. They find that none of the password “best practices” offers any real protection against these attacks. This observation is also supported by the study of Florencio and Herley [14], who examined the password policies of 75 different websites and found that their password policies address only guessing attacks and, in few cases, passwords reuse across sites.

The susceptibility to shoulder surfing and keystroke loggers is generally high when users log in from public computers [15]. A two-week-long field study [16] on real life Web usage found that half of the participants used public computers to access online accounts.

Thus, one of the most challenging tasks in user authentication today is to develop a text-based authentication scheme that satisfies the following requirements: i) Provides protection against observation attacks, ii) Offers good memorability, and iii) Provides sufficient entropy to prevent online brute-force attacks.

B. Contributions

In this paper, we explore the potential of cognitive questions in addressing these challenges by incorporating the scientific understanding of long-term memory to advance the security and usability properties that can be provided in an authentication system. In particular, we propose Q-A, a new authentication scheme in which a user registers by selecting
and answering six cognitive questions (e.g., “Who was your favorite high school teacher?”) from a set of twenty questions. During login, the user is shown one question at a time and asked to enter the letter at a random position in her answer. This process is repeated for all six questions, and correctly entering all six letters is required to authenticate. The contributions of Q-A are given below (see III for a detailed discussion).

**Usability.** A survey study [17] on 25 different password schemes found that memorability can be supported by leveraging pre-existing user-specific knowledge, rather than requiring users to memorize new information that is artificially constructed or random. This finding inspires our application of cognitive questions in Q-A, which gains usability advantages over other text-based password schemes [9, 11, 18] in the following way:

- Authentication secrets are easier to remember in Q-A, since it asks users for already known information, while the other schemes query for specifically memorized information.
- Psychology studies [19–21] reveal that it is difficult to remember information spontaneously without memory cues, where cognitive questions work as cues to retrieve the corresponding answers from a long-term memory [11, 22].
- Our scheme allows users to enter case-insensitive letters for authentication, while traditional textual passwords may contain numbers, upper-case letters, and special characters, which may require additional time and effort to enter, especially from portable devices (e.g., cellular phones).

In our study, users had a 100% memorability rate after one week, which was significantly higher than that for randomly assigned six-character passwords consisting of only lowercase letters. They reported high levels of satisfaction with the usability and security of Q-A, despite a long average time to log in.

**Security.** To the best of our knowledge, Q-A is the first text-based authentication scheme that addresses both internal and external observation attacks. The security features of our system are as follows:

- Typically, cognitive questions are prone to guessing by acquaintances attacks that exploit the knowledge about personal information of a user [23]. The analysis of Just and Aspinall [23] shows that three questions are sufficient to guarantee reasonable security for authentication based on cognitive questions. Our study on Q-A satisfied these security requirements, where a set of questions were carefully selected considering both usability and security metrics [23, 24], and each user was asked to answer six questions from this set to measure the usability of Q-A for a system with high security requirements.
- Q-A offers the variant response feature, where users’ entries vary across different login sessions to gain resilience against observation attacks.
- Although each security question offers relatively low entropy compared with a moderately strong password [23], selecting random letters from the answers to six different questions makes for a string of characters that is partially random and therefore hard to guess [7]. The theoretical password space (28 bits) offered by Q-A is sufficient to prevent online brute-force attacks [14].

With Q-A, we explore the idea of using information that is meaningful to users and already held in long-term memory for a primary authentication mechanism. By developing and evaluating the Q-A design, we show that such a mechanism can be built with reasonable usability and security properties.

We hope that this inspires researchers to further investigate ways to leverage such information for better schemes.

**II. Related Work**

In this section, we give an overview of the text-based authentication mechanisms and the proposed techniques to gain resilience against observation attacks.

**Traditional password.** Recall-based user-chosen textual password is the most widely used authentication scheme on the web. However, it is vulnerable to online guessing attacks [4, 5] that exploit password reuse and predictable patterns, since users use the same password on an average of six different accounts [11] and follow predictable strategies (e.g., using dictionary words or names) while creating passwords [2, 3].

To motivate users to create stronger passwords, different password restriction policies [2, 25] have been deployed, such as increasing minimum length of passwords, using combination of different types of characters, asking users to change passwords at regular intervals, and using password strength meters. However, in separate studies, Proctor et al. [26] and Shay et al. [2] reported that password restriction policies do not necessarily lead to more secure passwords. Rather, in some cases, they adversely affect the memorability.

**Mnemonic Password.** Kuo et al. [18] studied the guessing-resistance of user-selected mnemonic phrase based passwords, in which the user chooses a memorable phrase and uses a character (often the first letter) to represent each word in the phrase. Results [18] show that user-selected mnemonic passwords are slightly more resistant to brute-force attacks than traditional text-based passwords. Mnemonic passwords are found more predictable when users choose common phrases to create their passwords. A properly chosen dictionary may increase the success rate in guessing mnemonic passwords [18].

**System-assigned password.** Randomly assigned textual passwords provide better resilience against online guessing attacks in comparison to user-chosen text-based passwords [7]. Wright et al. [9] compared the usability of three different system-assigned textual password schemes: i) Recognition-based words, ii) Recall-based words, and iii) Recall-based random letters. In the recognition-based scheme, the user has to recognize a set of words, each word being displayed on screen amongst a set of distracter words. In the second scheme, users have to remember a list of four whole words, which serves as one password. In the last scheme, users are assigned random passwords of six lower-case letters. The password
What was the name of your first school?

Letter in the Second position of your answer: 

Fig. 1. A screenshot of a demo of the Q-A.

space for all the conditions are kept same (28 bits). Results for memorability show that word recall performs the worst and no significant difference is found between recognition and letter recall. Furthermore, the time required to login is significantly different for all pairings, and notably worst in the recognition condition.

System-assigned passphrase. Shay et al. [8] investigated the usability of system-assigned passphrases (space-delimited sets of natural language words), which did not show significant improvement over the system-assigned textual passwords of similar entropy. The study [8] indicates that a majority of participants in each condition wrote down their passwords/passphrases, and around half of the participants who did not write them down failed to recall their authentication secrets after two days.

PTP. Forget et al. [10, 11] proposed the Persuasive Text Passwords (PTP) scheme, in which, after a password is created by the user, PTP improves its security by placing randomly-chosen characters at random positions into the password. Users may shuffle to re-position the random characters until they find a suitable combination to memorize. PTP is resilient against attacks exploiting password reuse and predictable patterns. However, knowing that a system uses PTP and knowing how PTP works would allow attackers to refine their cracking strategies. The memorability for PTP is found to be just 25% when two random characters are inserted at random positions [11].

Cognitive question. The primary investigation of Furnell et al. [22] reported that 70% users preferred to have cognitive questions for authentication. However, most of the questions used in their study (e.g., “What is the name of your favorite relation?”, “What is your favorite shape?”) offer very limited entropy and thus can be easily guessed by attackers. Also, their approach is vulnerable to shoulder surfing and keystroke loggers. Later studies [23, 24, 27] performed comprehensive analysis on cognitive questions to figure out the usability and security of different types of questions. We have carefully considered their findings to design Q-A. A detailed discussion follows in the next section.

Resilience to observation attacks. Textual passwords are vulnerable to external observation attacks, such as shoulder surfing [28]. De Luca et al. [29] examined the impact of fake cursors in providing resilience against shoulder surfing when passwords are entered through an on-screen keyboard. However, results show that the users act predictably to identify their active cursor (e.g., moving the mouse cursor to the border of the interaction area or moving the mouse in small circles), which may make it easy for the shoulder surfer to find the real cursor and subsequently the authentication secret from on-screen keyboard entries.

Gaining the user’s credentials through malware (e.g., keystroke loggers, mouse loggers) is called an internal observation attack [13]. Text-based passwords are prone to keystroke loggers [15]. A few tricks have been proposed to hide passwords from keystroke loggers, such as typing fake characters in multiple text-boxes at the time of entering the password [15]. These tricks, however, require users to be conscious about keystroke loggers and take proactive measures, which is difficult [1, 3].

Conclusion and open problems. As we see from the above discussion, textual password schemes that provide better memorability are vulnerable to guessing attacks (e.g., traditional and mnemonic passwords). On the other hand, text-based passwords with higher resilience against guessing attacks suffer from memorability problems (e.g., system-assigned passwords and passphrases, PTP). Moreover, textual passwords are vulnerable to observation attacks.

Thus, despite a large body of research, it remains a critical challenge in password research to build an authentication system that offers both high memorability and guessing resilience, with robustness against observation attacks.

III. THE Q-A DESIGN AND SCIENTIFIC MOTIVATIONS

In this section, we first explain the basic design of Q-A. We then describe our approach to address the usability and security concerns with cognitive questions, followed by a detailed discussion on the usability and security features offered by Q-A.

Q-A is based on cognitive questions (e.g., “What is the name of your favorite childhood teacher?”), which inherently leverage existing long-term memories, information that is known to users based on their life experience. Q-A invokes the answers to cognitive questions in a novel way. At the time of registration, the user is shown a set of 20 carefully selected questions, of which she must select six questions to answer. These answers, in total, constitute her authentication secret. We choose the 20 questions carefully to ensure that each one asks for alphabetical answers with a high amount of entropy, such as the name of a person or a location.

During login, a user is presented with all six selected questions, one at a time. She does not have to enter the whole answers. Instead, for each question, the user is asked to enter a single letter from a particular position in her answer. Every time a user logs in, this position is randomly chosen by the system individually for each question. So, in a login session, a user may be asked to enter the letter in the second position for the first question, in the fourth position for the second question, and so on. These positions will vary in the subsequent login sessions. For example, if a user’s answer is “Anderson”, and at a given login session she is asked to enter the second letter of this answer, she has to enter ‘n’. In this way, a user has to correctly enter a letter for all six questions for a successful login.
A. Usability and Security of Cognitive Questions

In this section, we describe our approach in Q-A to address the usability and security concerns with cognitive questions.

1) Usability: Just and Aspinall defined three metrics to measure the usability of a cognitive question: i) Applicability, ii) Memorability, and iii) Repeatability [23]. This provides a useful guide to selecting appropriate questions for Q-A. We carefully considered these metrics while selecting questions for our study.

Applicability. Not every user can effectively answer every cognitive question. Users in our system choose any six questions from a set of twenty questions that they find most applicable to them. Offering a greater number of questions would further increase the applicability of the system.

Memorability. Research shows that a user can easily recall the answers of cognitive questions that are related to her long-term memory [23, 24]. Selecting such questions ensures that the user does not need to devote much cognitive effort in learning the Q-A passwords, as they are simply answers that she already knows.

A study by Schechter et al. reveals that the participants who used weak placeholder answers during the study failed to recall them later [24]. So, with a few basic restrictions in place to guard against poor answers (see III-C), it should typically be easier for a user to remember the real answer to a question than a weak placeholder answer ('Aab').

The study of Furnell et al. [22] shows that confusion between capital and lowercase letters is a prominent reason for making mistakes when answering a cognitive question. We address this by ignoring case in our scheme.

Repeatability. Just and Aspinall indicate that repeatability can be improved by providing users with the fixed format of answers to the questions that ask about dates or locations (e.g., different formats for date: ‘Feb-05, 1992’, ‘02-05-1992’, ‘02/05/1992’) [23]. To provide higher entropy, we recommend to avoid questions that ask for numerical answers, and this includes questions about specific dates. For location-related questions, instead of imposing any specific format on users, we prefer to be more specific with the questions to ensure repeatability. For example: instead of asking “Where did your father and mother meet?”, we would ask “In what city or town did your father and mother meet?” We recommend providing a fixed format for the answer to a question in which being specific with the question does not resolve the repeatability issues.

2) Security: The most important security concerns with cognitive questions include: i) User-created questions, ii) Guessing by acquaintances attacks, and iii) Common answers. We address these security issues in the following way.

User-created questions. If users are allowed to freely create their own questions, many users will not choose sufficiently secure questions [23]. On the other hand, it may have usability concerns for many users if the questions are strictly assigned by the system. Q-A balances these trade-offs by asking users to select any six questions from a larger set.

Guessing by acquaintances. Typically, cognitive questions are prone to targeted guessing attacks, in which attackers exploit the knowledge about personal information of a user [23, 24]. One’s mother’s maiden name and Social Security Number (SSN) in the US are particularly well-known examples of such questions. It is possible to select suitable questions, but still the amount of entropy in a single answer is typically lower than for a password [23, 24, 27].

Just and Aspinall [23] show that three questions are sufficient to guarantee reasonable security for cognitive-question-based authentication. In our study, we asked users to answer six questions to measure the usability of Q-A for a system with high security requirements.

Common answers. The answers to some cognitive questions are generally common among users. For example, blue or pink may be common answers to the question “What’s your favorite color?”. The prior studies [23, 24] have found that carefully selected questions can make common answers less of an issue for most users. The questions for Q-A were selected carefully based on the prior usability and security analysis on cognitive questions [23, 24, 27].

B. Usability Features and Memory Retrieval in Q-A

In this section, we state the usability advantages of Q-A from the perspective of cognitive psychology. Q-A offers two important usability advantages over other text-based authentication systems [9, 11, 13]:

- Known Information: Q-A queries for already known information, while the other schemes query for specifically memorized information.
- Memory Cues: Q-A provides users with the questions that work as cues to retrieve the corresponding answers from user’s memory, so as to log in successfully.

Known Information. From the viewpoint of cognitive psychology [30, 31], Q-A is closely tied with the concept of episodic memory [30, 31], which refers to the autobiographical event that the user can accurately recall, since she was part of it. Episodic memory incorporates the time and place of a personally meaningful event with the associated feeling and contextual information. For example, recalling the celebration of new millennium’s eve involves figuratively traveling back in time to precisely remember the place and the people associated with that event. Thus, cognitive-question-based authentication systems like Q-A aid password memorability, since a user does not need to memorize the answers specifically for authentication to an online account.

Memory Cues. Psychology research has shown that it is difficult to remember information spontaneously without memory cues [19, 21]. This suggests that authentication schemes should provide users with cues to aid memory retrieval. Ellis and Kvavilashvili state that memory cues support prospective memory [32], which is the ability to generate, retain, and later recall information in the appropriate context. Encoding specificity theory [31] postulates that the most effective cues are those that are present at the time of remembering. If semantic information about a word is processed at the time of learning, then that information can successfully be used to
cue memory. Thus, the word ‘Millennium Eve’ can only be used to cue memory of the word ‘New York’ if the subject encodes the semantic information linking the two objects at the time of encoding.

Generate-recognize theory [19] and Associative-strength theory [33] also focus on the effectiveness of cues in aiding memorability [20, 21]. Generate-recognize theory [19] speculates that retrieval is a two-step process, where in the generate phase, a list of candidate words is formed by searching the long-term memory. Then in the recognize phase, the list of words is evaluated to see if they can be recognized as the sought out memory. According to this theory, a cue can help not only in generating a relevant candidate list, but also in recognizing the appropriate word from that list. Associative-strength theory [33] states that a cue becomes effective if it has previously occurred with the remembered event in the past. The theory assumes that memory is structured as a network that connects all items in memory, and items in memory with stronger ties between them make better cues.

C. Security Features in Q-A

In this section, we describe the security features offered by Q-A.

1) Guessing resistance: The theoretical password space (28 bits) offered by Q-A is sufficient to prevent online brute-force attacks [14].

Theoretical password space. The questions in our scheme ask users for alphabetical answers (e.g., “what was the name of your first teacher?”), where the answers are case-insensitive. During login, the user is asked to enter the character at a given position in her answer. In this respect, the size of the domain for an alphabetical entry (26) is larger than a numerical entry (10). Thus, alphabetical answers provide higher resilience against online brute-force attacks [5, 34], in which an attacker tries all elements within a search space to obtain the password. The user has to enter a letter for each of the six questions. The space for this condition will therefore be $log_2(26)^6 \approx 28$ bits. Florencio and Herley’s study on security policies [14] suggests that 20 bits of theoretical password space suffices for an online environment with lockout rules.

Effective password space. Both in Q-A and in the study of password policies, only theoretical entropy is considered, though letters from random positions in the answers to cognitive questions may also have more effective entropy than user-selected passwords prone to dictionary attacks. In Q-A, the effective password space may vary for different questions, which requires to consider variation in answers in addition to general letter frequency. For example, the letter frequencies of names of people and locations will vary significantly by country and region. It would be an interesting area for future work to analyze the effective entropy of Q-A considering the letter frequency found in answers to different questions and the variation in answers in different languages, ethnicities, and countries.

Guard against poor answers. We have deployed some basic restrictions in our system to guard against poor answers (e.g., minimum three characters in an answer, no repeat answers between questions, at least two different letters in an answer), which might motivate users to give their real answers that, with the right questions, should have a large space of both possible and probable answers.

2) Observation attacks: Having authentication information vary across login sessions is known as variant response [17]. During login, the variant response feature makes our system more resilient against observation attacks like shoulder surfing, as compared to other text-based password schemes where the same set of characters is entered as password in every login session.

Shoulder surfing. When the user enters her credentials, either at registration or login, the answers are shown as asterisks or dots (as with regular password entry) to minimize the risk of shoulder surfing. During login, a user enters the letter at a given position in her answer, and to learn that letter and its position in the answer, the shoulder surfer needs to observe both the monitor and keyboard at a time, which has been found to be difficult in practice [28]. The requirements to observe the letters for all six questions further increase the hurdles for an attacker.

Even if a shoulder surfer can learn the letter and its position, he is likely to be asked to enter a letter of different position when he tries to log in as the user. Only a good guess of the entire answer for all six questions gives the attacker a reasonable chance of logging in.

The shoulder surfer may attempt to gain the user’s credentials when she enters the entire answer to a question at the time of registration. Although answers are shown as asterisks or dots (as with regular password entry) to reduce the risk of shoulder surfing, we recommend that the users register in a secure environment (e.g., avoiding public terminals) to ensure maximum security.

Keystroke and mouse loggers. Gaining a user’s authentication credentials through malware, such as keystroke loggers and mouse loggers, is called an internal observation attack [13]. A system provides resilience against keystroke/mouse loggers when the keyboard/mouse entries for authentication vary across subsequent login sessions [17]. Thus, the variant response feature in Q-A offers higher resilience against keystroke loggers as compared to a password system where the same set of letters is entered (using keyboard) during each login session. Our system is clearly resilient to mouse loggers, as we don’t use mouse input.

The security of Q-A can be further improved by asking users to answer more than six questions during registration and then drawing six at random for each authentication attempt. In this case, when an attacker tries to log in as a user, he may get different questions than the ones he gains through observation attacks. We will explore the usability of this approach in future work.

3) Social engineering attacks: Social engineering refers to the psychological manipulation of people so that they divulge confidential information [17]. Phishing [17] is a common form of social engineering attack.
Phishing. In a phishing attack, users are redirected to fraudulent websites to enter their credentials. In this case, the phishing victim will very likely get different questions from the ones she normally uses to log in, since a phisher would not typically have access to the user’s login sessions. This means that not only will the user enter information that is useless to the attacker, she may realize that something is wrong and end the session.

Fake calls. Users may be tricked to reveal credentials by any means, e.g., phone calls from a fake help desk or credit company [17]. Q-A does not provide direct resilience to social engineering when the users disclose their authentication secrets to the attacker. However, a site with high security requirements can use unique questions to avoid question and answer reuse and overlap between sites so that attackers cannot gain access to other accounts by acquiring password for a single account. We propose to explore this issue further in future work.

IV. STUDY DESIGN

Two prior text-based authentication systems [8, 9] aim to provide a usable solution to the security issues with passwords. Both papers compared their scheme with system-assigned random textual passwords (control passwords), where the results did not show significant improvement over control passwords in terms of memorability. We compare Q-A with control passwords and keep the theoretical password space the same (28 bits) for both conditions to examine whether Q-A offers better memorability in this respect.

In this study, we used a within-subjects design consisting of two experimental conditions (e.g., Q-A and control passwords). Using a within-subjects design controls for individual differences, and permitted the use of statistically stronger hypothesis tests. The experiments performed as part of this research received approval from our university’s Institutional Review Board (IRB) for human subject research.

A. Participants, Apparatus and Environment

For this experiment, we recruited 22 university students (6 women, 16 men) from diverse backgrounds, including majors from Biology, Engineering, Interdisciplinary Study, etc. The mean age of the participants was 27. They make regular use of the Internet and websites that require authentication. Each participant was compensated with a $10 gift card for participating in this study.

To administer this experiment, we created two realistic and distinct websites outfitted with the password scheme according to our two conditions: Q-A and control passwords. For both conditions, we used banking sites, but designed the interfaces with a different look and feel. Upon successful login at each bank site, the participants were forwarded to a dummy account overview page, to give them the feeling of using online banking services.

We carefully reviewed the prior usability and security studies on cognitive questions [22, 24, 27] to select the 20 questions for this study. The lab studies were conducted with one participant at a time to allow the researchers to observe the user’s interaction with the system.

B. Procedure

We conducted the experiment in two sessions, each lasting around 30 minutes. The second session took place one week after the first one to test memorization of the password. Note that the one-week delay reflects a common interval used in authentication studies (e.g., [9, 35, 36]). A field study [16] on real-life web usage found that one week is larger than the maximum average interval for a user between her subsequent logins to any of her important accounts [16]. Thus, we used this interval to examine the usability of our scheme.

1) Session 1: Before starting the experiment, we provided a consent form for the participants to read and sign, if they agreed. To compensate for the novelty effect, we asked the participants to perform one practice trial for authentication with Q-A. We did not collect data for this practice trial. The subsequent steps of the experiment are as follows:

Sign-up. During sign-up (we alternatively use the term registration) with Q-A, participants were shown a set of twenty questions, and they selected any six questions to answer, which constituted their password. Participants were also asked to sign-up with another site, where they were assigned a random six character password (control password).

To control for order effects, we employed counter balancing, so that all the participants would not see the schemes in the same order. Half of the participants used Q-A first, and the other half used the control password first.

Distraction. After sign-up, the participants were asked to count down in threes from a randomly chosen four-digit number for 45 seconds. This type of distraction flushes the textual working memory [37] and simulates a longer passage of time by focusing their attention on a separate, cognitively-difficult task. Participants were then given questionnaire that gathered demographic information.

Login (Recall-1). The participants were asked to log into each of those same sites, to demonstrate that the passwords had been memorized. Participants who were unable to reproduce their passwords during login, were shown the passwords.

2) Session 2: The second appointment took place one week after the first one. The participants were asked to log into each of the two sites (Recall-2). After they had finished, an anonymous paper-based survey was conducted to get their opinion on the overall experiences of using the authentication schemes. Participants were then compensated and thanked for their time.

V. RESULTS

In this section, we discuss the results of the user study described in [IV]. We label the login performance of participants in session 1 and session 2 as Recall-1 and Recall-2, respectively. Here, we tested the following hypotheses:
A. Hypothesis 1

H1a: The login success rate for Q-A and control passwords would not significantly differ in Recall-1.

H1b: The login success rate for Q-A would be significantly higher than that of control passwords in Recall-2.

In Q-A, users don’t have to memorize any new authentication secrets, as their password instead comes from cognitive questions related to their real life. However, in the control condition, the user is required to memorize a random string of characters as her password. In Recall-1, users were asked to enter their control passwords within a short period of learning it. So, we hypothesized that the login success rate for Q-A and control passwords would not significantly differ in Recall-1, but that Q-A would perform significantly better than control passwords in Recall-2, in terms of login success rate.

We observed a 100% login success rate for Q-A in both Recall-1 and Recall-2. In the control condition, login success rate was 91% in Recall-1 and 77% in Recall-2. Whether or not a participant successfully authenticated is a binary measure, so we use McNemar’s tests when we analyze the login success rate for our within-subjects experiment. Our analysis shows that login success rate did not differ significantly between Q-A and control conditions in Recall-1, $\chi^2(1, N = 22) = 0.5, p = 0.24.$ In Recall-2, however, the login success rate for Q-A was significantly higher than the control passwords, $\chi^2(1, N = 22) = 3.2, p < .05.$ H1a and H1b are supported by these results.

B. Hypothesis 2

H2: There would be a significant difference in login time between Q-A and control passwords in both Recall-1 and Recall-2.

Since Q-A requires entering the letter of a random position for as many as six answers, we hypothesized that for both Recall-1 and Recall-2, the login time for the control passwords would be significantly less than that of Q-A. Table III summarizes the results for login time, which shows that the mean login time in Q-A was 53.9 seconds in Recall-1 (median: 51 seconds) and 56.9 seconds in Recall-2 (median: 53 seconds). The mean login time (38.1 seconds in Recall-1, 43.7 seconds in Recall-2) in the control condition seems to be affected by the outliers, where the median login time was 11.5 seconds in Recall-1 and 13 seconds in Recall-2.

We did not get matched pair of subjects while comparing the time for successful logins in our study conditions, since a number of participants who succeeded to log in using Q-A, failed in control condition. So, instead of Wilcoxon signed-rank test, we used a Wilcoxon-Mann-Whitney test to evaluate the difference in login time between Q-A and control passwords. Wilcoxon tests are similar to t-tests, but make no assumptions about the distributions of the compared samples, which is appropriate to the count data in these conditions. In Recall-1, we found a significant difference in login time ($W = 72, p < 0.01$). The difference was significant in Recall-2 as well ($W = 350, p < 0.05$). All these findings provide enough evidence to support H2.

C. Hypothesis 3

H3: During login in Q-A, the mean time required to enter a letter of the given position would vary significantly for different positions in the answer in both Recall-1 and Recall-2.

The cognitive effort required to fetch a letter from the third position of an answer might be higher than entering a letter in the first position. So, we hypothesized that the mean time required to enter a letter would vary significantly for different positions in the answer.

We used a Kruskal-Wallis test for Hypothesis 3, which is similar to ANOVA, but does not make any assumption about the distributions of the compared samples, and is thus appropriate in this context. The Kruskal-Wallis test demonstrated that for Recall-1, the mean time required to enter a letter varied significantly for different positions in the answers, $\chi^2(4) = 15.32, p < 0.01.$ However, for Recall-2, the differences were not statistically significant, $\chi^2(4) = 4.79, p = 0.31.$ So, H3 is partially supported by our results.

D. Notable Findings

1) Number of attempts: A successful authentication in Q-A requires entering the correct letter for six questions, but we didn’t restrict the number of attempts a user could make before entering her authentication secret correctly. It allowed us tracking the number of mistakes a user committed before she was able to log in successfully. Q-A showed quite promising results in this respect.

In Recall-1, 82% participants succeeded on the first attempt to enter the correct letter for all six questions. The other participants made a mistake for only one question and entered the correct letter in the second attempt. In Recall-2, 73%

| Scheme | Study | Mean | Median | SD |
|--------|-------|------|--------|----|
| Q-A    | Registration | 116.6 | 103 | 43 |
|        | Recall-1     | 53.9 | 51 | 17.8 |
|        | Recall-2     | 56.9 | 53 | 20.5 |
| Control| Registration | 48.1 | 45.5 | 27.1 |
|        | Recall-1     | 38.1 | 11.5 | 70.8 |
|        | Recall-2     | 43.7 | 13 | 55 |
participants succeeded on the first attempt for all six questions. Of the other six participants (27%) who made a mistake in a question on the first attempt, four succeeded in the second attempt and the other two required no more than four attempts before entering the correct letter. One participant made mistakes in two questions; no other participant made any mistakes in more than one question in Recall-2.

For the control passwords in Recall-1, 82% of participants succeeded to log in on the first attempt. One participant required 10 attempts to log in successfully, as he did not notice that Caps Lock was on. Q-A overcomes this limitation, since the users’ responses are not case sensitive. In Recall-2, 68% of participants entered their control passwords correctly in the first attempt. The participants who were successfully authenticated after multiple attempts in Recall-2 required four attempts on average with a maximum of eight attempts.

2) Registration: In Q-A, participants were able to complete registration in less than two minutes on average (see Table I). The mean time to register in the control condition was 48.1 seconds. A Wilcoxon signed-rank test (appropriate for matched pair of subjects) reveals that there existed a significant difference in registration time between Q-A and control conditions ($W = 450.5, p < 0.01$).

**Correlations.** We were interested to see if the registration time for a participant would have any correlation with her login time and the required number of attempts for a successful login in either Recall-1 ($r = 0.25$) or Recall-2 ($r = 0.26$). Also, there existed no strong correlation between the registration time and the required number of attempts in Q-A for a successful login in either Recall-1 ($r = -0.05$) or in Recall-2 ($r = .20$).

**Number of mistakes.** During registration in Q-A, answers are shown as asterisks or dots to reduce the risk of shoulder surfing, and the users have to re-enter an answer to confirm. Our results show that users did not make any mistake when confirming the answers. We have deployed some basic restrictions in our system to guard against poor answers (e.g., minimum three characters in an answer, no repeat answers between questions, at least two different letters in an answer). In this respect, six participants attempted to enter an identical answer for multiple questions, and when they saw the error message they entered distinct answers for each question.

**E. User Opinion and Perception**

In order to gain an understanding of users’ perceptions on the usability and applicability of Q-A, we asked them to answer two sets of Likert scale questions at the end of the second session. We used ten-point Likert scales, where anchors were included on the bi-polar ends of the scale (1 indicating strong disagreement and 10 equalling strong agreement with the given statement). We reversed some of the questions to avoid bias; thus the scores marked with (*) were reversed before calculating the mode and median. A higher score always indicates a more positive result for Q-A. Since Likert scale data are ordinal, it is most appropriate to calculate mode and median for Likert-scale responses [38].

**Usability.** The perceptions of users on the usability of Q-A are illustrated in Table II. Users showed a high degree of satisfaction on the usability (e.g., memorability, ease of login) of our scheme, and they preferred Q-A over system-assigned textual passwords. The participants responded positively (i.e., mode and median were higher than neutral) about the ease of using Q-A either weekly or daily. Although they expressed concerns regarding the authentication time in Q-A, they reported that with practice they could log in quickly with this scheme.

**Applicability.** Table III shows users’ perceptions on the applicability of Q-A in different types of online accounts. Our findings suggest that most of the participants would strongly prefer to use Q-A for online accounts with high security requirements, such as banking and e-commerce accounts.

The participants were given an open-ended question at the end of second session to express their opinion about Q-A. In general, the feedbacks were positive and encouraging. They expressed high degree of satisfaction on the security features

**TABLE II**

**Questionnaire responses for the usability of Q-A. Scores are out of 10. * indicates that the scale was reversed.**

| Questions | Mode | Median |
|-----------|------|--------|
| Logging in using Q-A password was easy | 10 | 8.5 |
| Q-A passwords are easy to remember | 9 | 9 |
| With practice, I could quickly enter my Q-A password | 10 | 9 |
| *I found Q-A too time-consuming (i.e., I found Q-A to not take too much time) | 4 | 4.5 |
| *I prefer system-assigned textual passwords to Q-A (i.e., I prefer Q-A to system-assigned textual passwords) | 8 | 7 |
| I could easily use Q-A every day | 10 | 8 |
| I could easily use Q-A every week | 10 | 9 |

**TABLE III**

**Questionnaire responses for the applicability of Q-A in different online accounts. Scores are out of 10.**

| Online accounts | Mode | Median |
|-----------------|------|--------|
| Bank | 9 | 9 |
| Webmail | 9 | 6 |
| Social Networking | 5 | 5 |
| University Portal | 6 | 6.5 |
| E-commerce | 10 | 8 |

**TABLE IV**

**Questionnaire responses to the requirement of recording passwords in real life.**

| Scheme | Never | Rarely | Sometimes | Often | Always |
|--------|-------|--------|-----------|-------|--------|
| Q-A | 55% | 36% | 9% | 0% | 0% |
| Control | 0% | 14% | 46% | 36% | 4% |
of Q-A. For example, one participant reported, “I would use it for banks and other websites, where I use confidential info.” Several of them were interested to know if Q-A would be deployed commercially.

**Password recording.** All the participants reported that they did not write down their control nor Q-A passwords for this study. We also asked them if they would require writing down their Q-A or control passwords if they would use them in real life. The results (see Table IV) are quite promising in this respect: 55% of participants reported that they would never need to record their Q-A password, while 30% of participants would rarely need to. Only two (9%) of the participants mentioned that they would sometimes require to write down their Q-A password.

For control passwords, 46% of participants would sometimes require and 36% of participants would often need to record their password.

**VI. DISCUSSION**

The login success rate for Q-A was found to be 100% in both Recall-1 and Recall-2. Here we discuss the anticipated factors that might have played an important role to gain such high a performance during authentication.

- Q-A asks for already known information that are related to the long term memory of a user. So, the user does not have to memorize any artificial information as her authentication secret.
- Q-A provides users with the flexibility to choose any six questions from a set of twenty, which they find most applicable to them.
- The basic restrictions (see III-C) should have motivated users to enter the correct answer instead of a weak placeholder one (‘Aab’). Real answers to cognitive questions have been shown to be more memorable than placeholder answers [24].
- Being specific with the question helps to accurately recall the answer in Q-A. For example: instead of asking “Where did your father and mother meet?”, we would ask “In what city or town did your father and mother meet?”
- Q-A makes users focus on fetching a letter from the given position in her answer, which reduces the chance of typing mistakes that occur when they have to enter the whole answer.
- Q-A is case-insensitive, while confusion between capital and lowercase letters has been shown to be a prominent reason for making mistakes when answering cognitive questions [22].

**A. Limitations and Ecological Validity**

Our participants were young and university educated, which represents a large number of frequent Web users, but may not generalize to the entire population. As the study was performed in a lab setting, we were only able to gather data from 22 participants.

Although field studies may provide superior ecological validity, lab studies have been preferred to examine brain-powered memorability of passwords [39]. Moreover, lab studies have the advantage of taking place in a controlled setting, which helps to establish performance bounds and figure out whether field tests are worthwhile in future research.

Our results for login time are conservative since they reflect initial use. As noted in existing research [13], login time likely decreases with frequent use of a scheme. Chiasson et al. [40] find that users get more attentive while entering passwords in a lab study, which can contribute to less login error and higher login time than the casual login attempts in real-life scenario. Further long-term studies in a real life setting could provide additional insights on the training effect.

**VII. CONCLUSION AND FUTURE WORK**

Our study on Q-A finds that cognitive questions possess good possibilities in primary authentication in terms of both usability and security. We note that in addition to providing sufficient entropy to prevent online guessing attacks, Q-A is resilient to both internal and external observation attacks. Memorability in Q-A was found to be 100% in our study. Users’ feedbacks reveal that they are highly satisfied with the memorability and security of this scheme, which would be most appropriate for online accounts with high security requirements (e.g., online banking, e-commerce [16]).

Now that we have observed promising memorability for single Q-A password in a lab setting, it seems reasonable to plan for a field study with larger and more diverse populations in order to examine if cognitive questions can provide a usable solution to the memorability and interference problems with multiple passwords.

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