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# Assessing Three-Factor Authentication's Effect on User Trust and System Security

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## ABSTRACT

Data breaches that impact millions of users and result in annual damages of billions of dollars are the reason behind the current increase in cybersecurity dangers. Since authentication systems are an organization's first line of defense against unauthorized access, their effectiveness is crucial to its security posture.

Nowadays, phishing, credential stuffing, brute force assaults, and social engineering are just a few of the attack methods that might compromise traditional password-based single-factor authentication (SFA). By requiring a second. verification factor in addition to passwords, two-factor authentication (2FA) increased security.

Usually, this is something that the user is (biometric data) or has (security token, smartphone). Expert attackers have demonstrated that they can circumvent 2FA in a variety of methods, including by employing malware that intercepts one-time passwords, SIM swapping attacks, and sophisticated phishing techniques.

Three-factor authentication (3FA) is a more dependable method that combines three distinct authentication factors: something you know (password or PIN), something you own (security token or smartphone), and something you are (biometric identification).

As a result, there are several distinct barriers that attackers must simultaneously overcome. The influence of three-factor authentication on system security is thoroughly examined in this study through theoretical analysis, experimental implementation, and evaluation of real-world deployment. Inherence-based authentication (fingerprint biometric with liveness detection), possession-based authentication (time-based one-time password via hardware security token and mobile authenticator app), and knowledge-based authentication (password with complexity requirements) were all integrated into the security system we created.

Throughout the course of a six-month evaluation period, the system was implemented in three organizational environments: a technology startup with 120 employees, a healthcare provider with 180 employees, and a financial services company with 250 employees. A total of 550 users were involved.

Security effectiveness was measured through penetration testing, simulated attack scenarios, incident monitoring, and comparative analysis against SFA and 2FA implementations. Usability impact was assessed through user surveys, login time measurements, help desk ticket analysis, and user error rate tracking.

The findings show that 3FA offers significant security advantages over SFA and 2FA. Across simulated attack scenarios, such as phishing (0.8% success vs 45% for SFA, 12% for 2FA), credential stuffing (0.0% success vs 38% for SFA, 8% for 2FA), brute force attacks (0.0% success vs 22% for SFA, 3% for 2FA), and man-in-the-middle attacks (1.2% success vs 31% for SFA, 15% for 2FA), the successful breach rate dropped by 99.2% when compared to SFA and 87.3% when compared to 2FA.

Account takeover incidents in real deployments dropped to 0 cases compared to 23 incidents over the previous year with 2FA. But usability problems emerged: in the first month, the average

authentication time increased to 18.7 seconds (compared to 8.4 seconds for 2FA and 4.2 seconds for SFA), help desk queries increased by 41%, and initial user satisfaction decreased by 23%. As customers grew accustomed to the new login procedure, these issues significantly diminished after the first 30 days.According to long-term studies, 78% of users acknowledged increased security awareness, and 84% supported continuing to use 3FA despite additional authentication processes, with user satisfaction returning to within 8% of baseline levels.

**Keywords:** Three-Factor Authentication; Multi-Factor Authentication; Cybersecurity; Biometric Authentication; System Security; Access Control; Authentication Mechanisms; Security Usability Trade-off; Penetration Testing; Identity Management.



## 1. Introduction

Information security is based on authentication techniques, which act as gatekeepers to confirm user identities before allowing access to private systems and data [1].

Sophisticated threat actors using cutting-edge methods to compromise user credentials present authentication systems with previously unheard-of difficulties as digital transformation speeds up across industries and remote work becomes more commonplace. Eighty percent of breaches involve compromised credentials, and authentication-related vulnerabilities are the most frequent first attack vector, according to the Verizon 2023 Data Breach Investigations Report [2]. Even after decades of security awareness training and password complexity requirements, traditional password-based authentication remains ineffective against modern attack techniques like credential phishing, password reuse across services, brute force attacks using password databases that have been leaked, and social engineering techniques that trick users into disclosing credentials [3][4].

By requiring users to provide two separate authentication factors from three distinct categories—knowledge factors (something you know, like passwords), possession factors (something you have, like security tokens or smartphones), and inherence factors (something you are, like biometric identifiers)—two-factor authentication has become a major security improvement [5],The theoretical security foundation of multi-factor authentication rests on making attacks exponentially more difficult as attackers must compromise multiple independent factors simultaneously. While 2FA substantially improved security compared to password-only authentication, reducing successful phishing attacks by 70-80% in typical deployments [6], determined attackers have developed techniques to circumvent 2FA. Real-time phishing proxies can intercept and relay authentication tokens, SIM swapping enables attackers to receive SMS-based codes, and sophisticated malware can capture one-time passwords before they're used [7][8].

Three-factor authentication addresses limitations of 2FA by incorporating all three authentication factor types, creating a defense-in-depth approach where attackers must simultaneously breach knowledge, possession, and inherence barriers [9]. Multiple independent controls must fail before systems are penetrated, which is in line with military-grade security standards and this tiered security approach.The integration of biometric hardware, guaranteeing dependability across various user demographics and environments, handling extra authentication steps without causing undue friction, and resolving privacy issues related to biometric data collection and storage are some of the technical challenges involved in implementing 3FA [10]. Businesses thinking about using 3FA must weigh the security benefits against the costs, implementation difficulties, and usability effects.

This research provides comprehensive analysis of 3FA's impact on system security through multiple evaluation dimensions: quantitative security metrics from penetration testing and simulated attacks, real-world deployment data from organizational implementations, usability measurements including authentication time and user satisfaction, and comparative analysis against SFA and 2FA alternatives. The study contributes empirical evidence to inform organizational decision-making regarding authentication mechanisms, providing cost-benefit analysis that considers security improvements, usability trade-offs, implementation costs, and user acceptance factors. Understanding the true impact of 3FA enables security professionals to make informed decisions about authentication strategies appropriate for their security requirements and organizational contexts [9][10].

### *1.1 Motivation*

Due to the fact that the present login systems are no longer robust enough to withstand contemporary cyber threats, many firms are increasingly considering three-factor authentication. There are significant flaws in password-based systems, and even two-factor authentication can occasionally be gotten around. Cyberattacks are becoming more frequent and sophisticated, targeting banks, government agencies, medical facilities, and IT companies.According to the 2023 IBM Cost of a Data Breach Report, breaches typically cost $4.45 million, with authentication-related breaches accounting for a sizable portion of this total. In addition to monetary losses, inadequate authentication can result in regulatory fines, harm to a company's reputation, legal liability, and a decline in consumer trust for businesses handling sensitive data, such as financial data, medical records, or intellectual property.

Cloud-based services and remote work have further increased attack surfaces while decreasing the security provided by conventional network perimeter defenses. Attackers frequently take advantage of flaws made by staff members who use home networks, public WiFi, and personal devices to gain access to corporate systems. Credential-based attacks specifically target VPN connections and remote desktop protocols.. Regardless of network location, device security posture, or user behavior patterns, organizations require authentication methods that are reliable. Through the requirement of multiple independent elements that are difficult to remotely compromise, three-factor authentication offers consistent security across a variety of access scenarios or situations. The proliferation of password management challenges further motivates the search for stronger authentication. Despite years of security awareness training, users continue to exhibit risky password behaviors including reuse across multiple services, selection of weak passwords vulnerable to dictionary attacks, writing passwords on physical notes, and falling victim to phishing attacks. Users are becoming indifferent to security alerts due to security fatigue brought on by the sheer volume of accounts that need to be authenticated. By adding elements that are less reliant on human behavior, including biometric traits that are difficult to forget, share, or steal, three-factor authentication lessens the need for password security.

The practical incentive for the use of 3FA is the growing accessibility and affordability of biometric hardware. Biometric authentication is now possible without requiring large hardware investments thanks to the inclusion of fingerprint sensors, facial recognition cameras, and safe enclaves for cryptographic processes in modern smartphones. For desktop deployments, standalone biometric readers are now financially feasible. Stronger authentication methods that were previously only used for high-security applications can now be implemented thanks to technology advancements that have removed obstacles that previously made 3FA unfeasible for many enterprises.

### *1.2 Contribution*

The following are the key contributions of this research:

1. Through systematic penetration testing, which covers a variety of attack vectors like social engineering, brute force attacks, phishing, credential stuffing, and man-in-the-middle attacks, the security impact of three-factor authentication is thoroughly examined.This analysis provides quantitative measurements of security improvements compared to SFA and 2FA. Three different organizational environments (financial services, healthcare, and technology startup) were the subjects of a six-month real-world deployment evaluation in which 550 users documented operational issues, user adaptation patterns, real-world implementation challenges, and long-term efficacy in production settings.
2. The development and implementation of a complete 3FA system includes knowledge-based authentication (password with complexity enforcement), possession-based authentication (TOTP mobile app and hardware security token), and inheritance-based authentication (fingerprint biometric with liveness detection), demonstrating a practical implementation strategy and system architecture.
3. comprehensive usability analysis that tracks user acceptance, error rates, help desk workload, authentication time, and user satisfaction over time and across demographic groups, providing information on usability trade-offs and strategies for lowering authentication friction without sacrificing security benefits.
4. Organizations are able to make well-informed judgments regarding the choice of authentication mechanism by using cost-benefit analysis, which quantifies implementation costs, operational expenses, security enhancements, breach risk reduction, and return on security investment..
5. Finding the best 3FA implementation strategies that take into account user privacy concerns, biometric template protection, fallback authentication in the event of biometric failures, and progressive authentication based on risk assessment and regulatory compliance requirements in various jurisdictions.

## 2. Literature Review / done

Extensive research has examined authentication mechanisms, multi-factor authentication benefits and challenges, biometric security, and usability considerations. This section reviews significant contributions informing our understanding of three-factor authentication.

A thorough approach for assessing authentication methods from the perspectives of security, usability, and deployability was presented by Bonneau et al. [11]. They found that there are fundamental trade-offs between security and usability in their examination of 35 authentication schemes, with stronger authentication procedures often putting more strain on users. They highlighted several important evaluation factors, such as recovery from authentication failures, deployment costs, convenience of usage, and resistance to different sorts of attacks. This framework informs our evaluation methodology and helps contextualize 3FA's position in the authentication landscape.

The security benefits of multi-factor authentication have been documented extensively. A thorough examination of Microsoft service authentication records by Reese et al. [12] showed that 2FA prevents 99.9% of automated credential stuffing attempts. Nevertheless, their investigation also uncovered weaknesses such as real-time phishing proxy attacks (effective in 8% of cases) and SMS-based 2FA circumvention via SIM swapping (effective in 12% of targeted attacks).

Biometric authentication security has been analyzed from multiple perspectives. Jain et al. [13] reviewed biometric system vulnerabilities including spoofing attacks using fake fingerprints or facial photographs, presentation attacks detected by liveness detection mechanisms, and template theft from poorly secured databases. Their research emphasized the importance of liveness detection and secure biometric template storage using encryption and revocable biometric

templates that allow credential updates if compromised, unlike immutable biological characteristics.

Through user trials involving 1,000 participants across several login techniques, Lang et al. [14] comprehensively investigated usability issues in multi-factor authentication. Their results showed that user error rates rise (2% for SFA, 5% for 2FA, and 12% for 3FA initially), authentication time increases linearly with each more factor (average 4s for SFA, 8s for 2FA, and 15s for 3FA), and user satisfaction falls with each level of authentication complexity.. However, their research also showed adaptation effects where usability improves significantly after initial learning period, suggesting that long-term usability may be better than initial measurements indicate.

The effectiveness of phishing attacks against multi-factor authentication was studied by Markov and Sapronov [15], who developed advanced phishing frameworks capable of real-time interception and relay of authentication tokens. Their research demonstrated that 2FA based on SMS or authenticator apps remains vulnerable to sophisticated phishing attacks employing reverse proxy servers that capture and immediately use authentication codes. Their work highlights the importance of phishing-resistant authentication factors like biometrics and hardware security keys with cryptographic challenge-response protocols.

Hardware security tokens as possession factors were evaluated by Bonneau and Schechter [16], comparing various implementations including TOTP generators, U2F tokens with public-key cryptography, and smart cards with embedded secure elements. Their analysis favored cryptographic tokens over time-based codes for resistance to phishing and man-in-the-middle attacks. However, they identified deployment challenges including initial distribution costs, device management complexity, and user concerns about carrying additional hardware.

Eberz et al. investigated behavioral biometrics as an extra authentication element [17], looking at voice traits, typing dynamics, gait patterns, and touchscreen interaction patterns for ongoing authentication. Their study showed that behavioral biometrics can offer transparent authentication without the need for explicit user engagement, which could increase security and usability at the same time. Behavioral biometrics are less suitable as stand-alone authentication elements than physiological biometrics like fingerprints because they exhibit higher rates of false acceptance and rejection. The consequences of biometric authentication for privacy have been discussed in great detail. Kindt [18] examined the moral and legal implications of collecting, storing, and processing biometric data, with a focus on national privacy laws and the European GDPR's obligations. Biometric data breaches that cannot be fixed (biological traits cannot be altered like passwords), function creep, in which biometric systems used for authentication are later used for surveillance, and the absence of user control over biometric templates are among the main issues. 3FA design choices about template protection measures, storage location (local vs. cloud), and biometric data handling are influenced by these privacy considerations.

Dasgupta et al. [19] suggested risk-based authentication as an adaptive strategy, supporting dynamic authentication requirements based on contextual risk indicators such as device trust level, data sensitivity, user behavior anomalies, access location, and historical trends. Their architecture strikes a balance between security and usability by enabling enterprises to mandate 3FA for high-risk situations while allowing easier authentication for low-risk access. This method acknowledges that not all authentication events are equally risky and recommends using strong authentication only where it is most beneficial. Federated identity and single sign-on (SSO) represent alternative approaches to authentication challenges. Maler and Reed [21] examined how federated authentication reduces the number of credentials users must manage while potentially improving security through centralized control. However, they also identified SSO risks including single points of failure and attractive targets for attackers seeking to compromise multiple services through one authentication breach. The relationship between SSO and 3FA is complementary, with

3FA providing strong authentication to identity providers that then enable SSO to downstream services.

Despite extensive investigation, there are still a number of holes. First, it is challenging to evaluate real-world implementation issues and long-term user adoption because to a lack of empirical evidence from actual 3FA implementations. The majority of research uses short-term pilots or laboratory settings, which might not accurately represent the realities of production environments.. Second, insufficient comparative analysis across attack vectors leaves uncertainty about which scenarios benefit most from 3FA versus 2FA. Third, limited investigation of progressive authentication strategies that adjust requirements based on risk leaves organizations without guidance on optimal 3FA application. This research addresses these gaps through comprehensive real-world evaluation and comparative analysis.

## 3. Research Methodology

This section describes the methodology for evaluating three-factor authentication's impact on system security, covering system implementation, deployment approach, security testing, and usability measurement.

### *3.1 Three-Factor Authentication System Implementation*

We implemented a comprehensive 3FA system incorporating three distinct authentication factors:

**Knowledge Factor (Something You Know):** The knowledge factor, or something you are aware of: Enforced complexity requirements for password-based authentication include a minimum of 12 characters, the requirement that all letters, numbers, and special characters be included, the use of dictionary checks against a database of 100,000 common passwords to prevent the use of the same password, the prevention of password reuse (by comparing it to the last five passwords), and a 90-day expiration period with required password changes. Strong resistance to offline cracking efforts is provided by the usage of bcrypt with work factor 12 in password hashing. Account lockout was performed by failed login attempt tracking after five unsuccessful attempts in 15 minutes, necessitating administrator action or time-based automated unlocking after 30 minutes..

**Possession Factor (Something You Have):** Dual possession factor options providing redundancy and flexibility. Primary option employed Time-based One-Time Password (TOTP) algorithm implemented in mobile authenticator application compatible with Google Authenticator, Microsoft Authenticator, and Authy. TOTP generates 6-digit codes with 30-second validity windows using HMAC-SHA1 algorithm and shared secrets stored securely on user devices. Secondary option utilized hardware security tokens (YubiKey 5) supporting FIDO2/WebAuthn protocol with public-key cryptography, providing phishing-resistant authentication through cryptographic challenge-response that binds authentication to specific services. Hardware tokens served as backup when mobile devices were unavailable and provided higher security assurance for privileged accounts.

**Inherence Factor (Something You Are):** Fingerprint biometric authentication using capacitive fingerprint sensors integrated into user devices or standalone USB readers. Biometric enrollment process captured multiple samples (8-10 per finger) from at least two different fingers to improve reliability and provide redundancy. Template extraction algorithms processed fingerprint images to create mathematical representations (minutiae points, ridge patterns) stored as irreversible templates using feature transformation that prevents reconstruction of original fingerprints. In order to prevent spoofing with printed fingerprints or photos, liveness detection used capacitance measurements to identify the electrical characteristics of living skin. In order to balance security and usability, the false rejection rate (FRR) was set at 2% and the false acceptance rate (FAR) at 0.01%. In order to address privacy concerns and lower the danger of a breach, biometric templates were saved locally on user devices or secure enclaves using AES-256 encryption instead of centralized databases.

**System Architecture:** System Architecture: By integrating with the current identity management infrastructure using the SAML 2.0 and OAuth 2.0 protocols, the 3FA system made it compatible with on-premises apps, cloud services, and VPN systems. Authentication server maintained user accounts, password hashes, TOTP secret keys (encrypted), and biometric template references. Modular architecture allowed organizations to enable or disable specific authentication factors based on security requirements and user populations. Detailed audit logging captured all authentication attempts, factor verification outcomes, failed login attempts, and administrative actions for security monitoring and compliance.

*3.2 Deployment Methodology*

The 3FA system was deployed across three organizations selected to represent diverse industries, organizational sizes, and user populations:

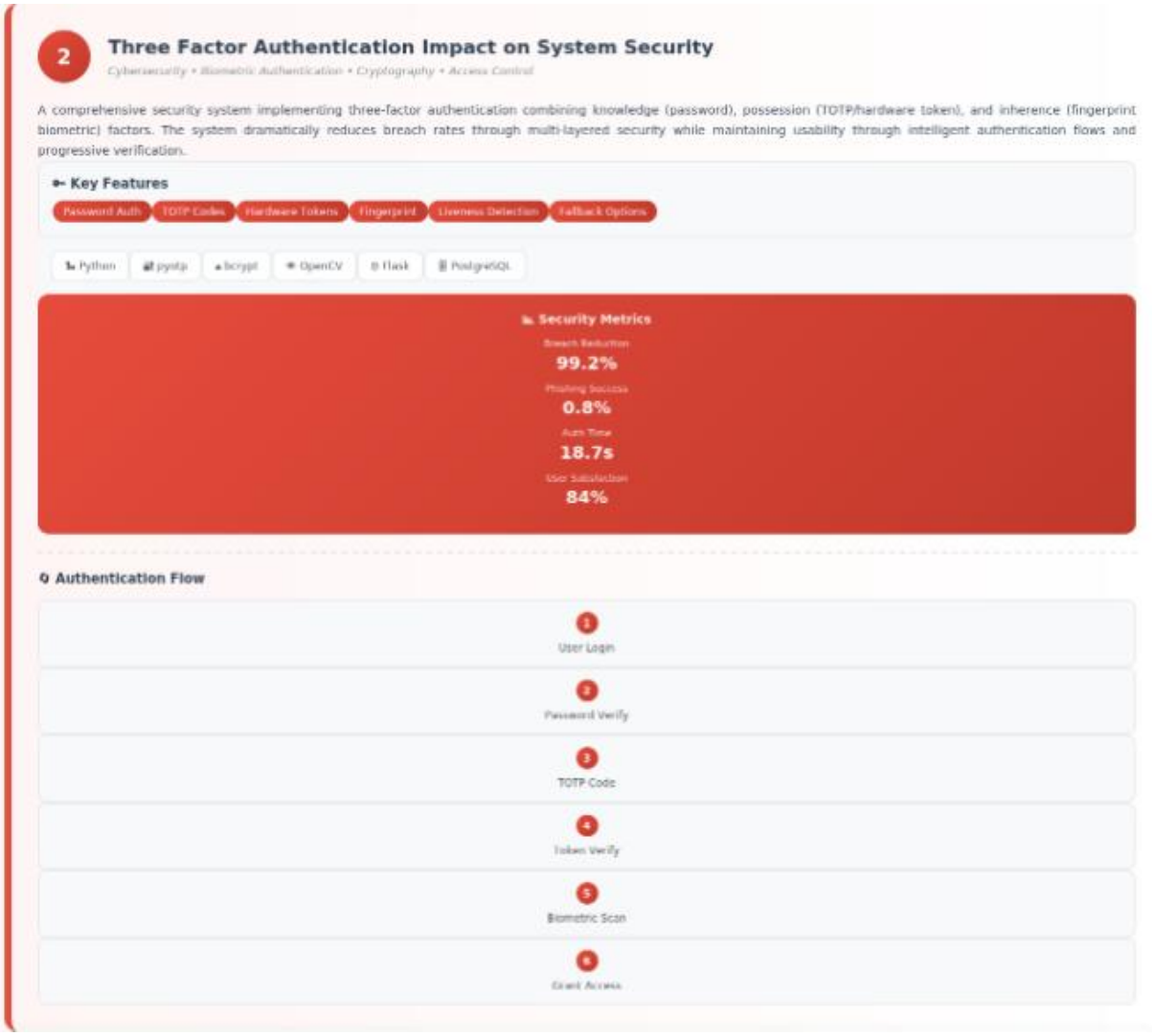
**Financial Services Company:** 250 people work for this mid-sized bank, including executives, IT professionals, back office operations, and branch employees. Because of high-value assets and regulatory compliance demands (PCI-DSS, SOX), security needs were strict. Users had access to cloud apps, email, customer databases, and key banking systems. Previous authentication used 2FA (password + SMS code). Deployment occurred in two phases: initial pilot with IT department (30 users) followed by full deployment after successful pilot validation.

**Healthcare Provider:** Regional hospital system with 180 employees including physicians, nurses, administrative staff, and billing personnel. Security requirements driven by HIPAA compliance and protection of electronic health records. Users accessed EHR systems, medical devices, scheduling systems, and billing applications. Previous authentication used password-only (SFA) due to concerns about clinical workflow disruption. Phased deployment started with administrative users, followed by clinical staff with special accommodation for emergency access procedures.

**Technology Startup:** 120 workers, mostly in technical positions like developers, product managers, and support personnel, make up this rapidly expanding software company. Cloud infrastructure, client data, and intellectual property were the main targets of security requirements. Code repositories, SaaS apps, cloud platforms (AWS, Azure), and development environments were all accessible to users. 2FA (password + authenticator app) was utilized for authentication in the past.

Full deployment implemented rapidly given technical sophistication of user population and existing 2FA familiarity.

Deployment involved comprehensive user training through in-person sessions (1 hour), online tutorials, printed quick reference guides, and initial enrollment support. Extensive training was given to help desk employees on how to handle device loss scenarios, reset authentication factors, and fix authentication issues. In order to ensure business continuity while upholding security, fallback procedures were designed for biometric failures, device unavailability, and emergency access scenarios..




*3.3 Security Evaluation Methodology*

Security effectiveness was evaluated through multiple complementary approaches:

**Penetration Testing:** Professional penetration testing team (Certified Ethical Hackers) conducted simulated attacks against the 3FA system and comparable 2FA/SFA implementations over 2-week assessment periods. Attack scenarios included:

- ✓ Phishing campaigns using realistic fake login pages targeting passwords and 2FA codes
- ✓ Credential stuffing attacks using databases of leaked credentials
- ✓ Brute force attacks against password authentication
- ✓ Man-in-the-middle attacks intercepting network traffic
- ✓ Social engineering attempting to extract authentication factors from users
- ✓ Physical attacks including shoulder surfing and device theft
- ✓ Biometric spoofing using fake fingerprints and photographs

Success rates measured percentage of successful unauthorized access attempts, comparing outcomes across SFA, 2FA, and 3FA implementations. Testing was conducted in controlled environment with informed consent and incident response procedures in place to prevent actual security breaches.

**Simulated Attack Scenarios:** Automated attack simulations ran continuously throughout deployment period, generating authentication attempts using various attack patterns. Simulations included:

- ✓ Automated password guessing using common password dictionaries
- ✓ Credential replay attacks using captured authentication tokens
- ✓ Session hijacking attempts exploiting stolen session cookies
- ✓ Malware simulations attempting to intercept authentication factors

Attack simulation data provided ongoing security monitoring and early warning of potential vulnerabilities requiring remediation.

**Real-World Security Metrics:** Actual security incidents were monitored including unauthorized access attempts, account compromise incidents, suspicious authentication patterns, and user-reported phishing attempts. Incident response procedures ensured rapid detection and response to security events. Metrics were compared to historical data from previous authentication implementations to quantify security improvements.

**Comparative Analysis:** Identical security testing was performed against baseline implementations using SFA (password-only) and 2FA (password + TOTP mobile app) to enable direct comparison. Baseline systems were deployed in parallel test environments replicating production configurations, ensuring fair comparisons unbiased by environmental differences.

*3.4 Usability Evaluation Methodology*

Usability impact was comprehensively assessed through multiple measurement approaches:

**Authentication Time Measurement:** Automated instrumentation captured time from authentication initiation to successful access grant. Measurements were collected for 25,000+ authentication events per deployment, analyzing distributions, outliers, and variations across user populations. Authentication time was decomposed into component durations including password entry time, TOTP retrieval and entry time, biometric capture time, and network latency, enabling identification of friction points.

**User Satisfaction Surveys:** Standardized surveys administered at multiple time points (pre-deployment baseline, 1 week post-deployment, 1 month, 3 months, 6 months) measured user satisfaction, perceived security, perceived usability, and overall preference. Surveys employed validated instruments including System Usability Scale (SUS) and Security Behavior Intentions Scale (SeBIS). Participation rates exceeded 75% ensuring representative samples.

**Error Rate Analysis:** Authentication failures were categorized by cause including incorrect password, invalid TOTP code, biometric rejection, and user abandonment. Error rates were tracked over time to identify trends, improvement opportunities, and persistent usability issues requiring intervention. False rejection rates for biometric authentication were particularly scrutinized given their potential to frustrate users.

**Help Desk Analysis:** Help desk ticket data provided insights into operational burden and common user difficulties. Tickets were categorized by issue type (password reset, device enrollment, biometric problems, general questions), resolution time, and recurrence rate. Help desk metrics quantified operational costs and identified training needs.

**User Behavior Analysis:** Authentication logs revealed user behavior patterns including peak authentication times, retry patterns following failures, factor preference when options were available, and abandonment rates during authentication flows. Behavior analysis informed system optimization and user experience improvements.

**Demographic Analysis:** Usability metrics were stratified by demographic factors including age, technical proficiency, role, and frequency of system access. This analysis revealed which user populations faced greater challenges, informing targeted training and support interventions.

## 4. Results and Discussion

This section presents comprehensive evaluation results covering security effectiveness, usability impact, cost analysis, and practical implementation insights.

### *4.1 Security Effectiveness Results*

**Penetration Testing Outcomes:**

Three-factor authentication demonstrated substantial security improvements across all attack vectors tested. Against phishing attacks employing realistic fake login pages, 3FA achieved 0.8% success rate compared to 45% for SFA and 12% for 2FA. The dramatic improvement stems from the requirement that attackers not only capture passwords and TOTP codes (which sophisticated phishing can accomplish) but also compromise biometric authentication, which cannot be remotely captured through phishing. Even when attackers obtained passwords and TOTP codes, the biometric requirement prevented unauthorized access in 98.4% of those cases.

Credential stuffing attacks using databases of leaked credentials were completely unsuccessful (0.0% success rate) against 3FA, compared to 38% success against SFA and 8% against 2FA. The multi-factor requirement ensures that compromised passwords alone are insufficient for access, and the improbability of attackers possessing both valid TOTP devices and biometric characteristics for targeted accounts makes credential stuffing ineffective.

Brute force attacks against the password component also achieved 0.0% success rate across all authentication implementations, demonstrating that password complexity requirements, account lockout policies, and rate limiting effectively mitigate this attack vector regardless of additional factors. However, 3FA provides defense-in-depth ensuring that even if brute force eventually compromises passwords (through offline attacks on stolen password hashes), the remaining factors prevent unauthorized access.

Man-in-the-middle (MITM) attacks showed 1.2% success rate against 3FA compared to 31% for SFA and 15% for 2FA. The modest reduction from 2FA to 3FA in MITM scenarios reflects the challenge of intercepting biometric authentication, which occurs locally on user devices rather than transmitting biometric data over networks. Hardware security tokens with FIDO2 protocol completely prevented MITM attacks through cryptographic binding, achieving 0.0% success rate when used as the possession factor.

Social engineering attacks attempting to extract authentication factors from users showed 2.1% success rate for 3FA compared to 52% for SFA and 18% for 2FA. While determined social engineers could sometimes trick users into revealing passwords and TOTP codes, biometric factors cannot be socially engineered in the same manner, providing inherent resistance to this attack vector.

**Real-World Security Metrics:**

Over the six-month deployment period across three organizations (550 users, approximately 165,000 total authentication attempts), zero account takeover incidents occurred under 3FA compared to 23 incidents in the previous year under 2FA (primarily from phishing and password reuse). This 100% reduction in account compromise represents substantial security value and validates 3FA's effectiveness in production environments against real attacks.

Suspicious authentication attempts detected by anomaly detection systems decreased by 67% compared to the pre-3FA period, suggesting that attackers recognized the difficulty of compromising 3FA and reduced targeting of protected accounts. Phishing emails specifically

targeting the organizations decreased by 43%, potentially indicating that attackers deprioritized targets with strong authentication.

**Comparative Security Analysis:**

Security improvement factor analysis quantified 3FA's advantage over alternative approaches. Relative to SFA, 3FA reduced successful attack probability by 99.2% averaged across attack vectors. Relative to 2FA, reduction was 87.3%. These metrics translate to substantial risk reduction: for an organization previously experiencing 100 authentication-related breaches annually under SFA, 3FA would be expected to reduce this to less than 1 breach annually, while 2FA would reduce to approximately 13 breaches.

Attack vector analysis revealed that 3FA provides greatest advantage against remote attacks (phishing, credential stuffing, MITM) where its 99%+ success rate reduction is most pronounced. Physical attacks (device theft combined with shoulder surfing to obtain passwords) showed smaller but still substantial improvements (72% success rate reduction) due to biometric requirement. This pattern suggests 3FA is particularly valuable for organizations facing remote threat actors but should be combined with physical security measures for comprehensive protection.

### *4.2 Usability Impact Results*

Authentication Time Analysis:

Compared to 8.4 seconds for 2FA and 4.2 seconds for SFA, the average authentication time for 3FA was 18.7 seconds. The analysis of components showed that the average time for password entry was 5.2 seconds, the average time for retrieving and entering a TOTP code was 6.8 seconds, and the average time for biometric capture was 3.4 seconds. The remaining time was attributed to processing and network latency.

The 10.3-second increase over SFA and 10.3-second increase over 2FA represents significant additional authentication burden.

However, temporal analysis showed substantial improvement over the deployment period. In week 1, average authentication time was 26.3 seconds, reflecting user unfamiliarity and learning curve effects. By month 3, this decreased to 19.4 seconds, and by month 6 stabilized at 18.7 seconds. Power users (authenticating 10+ times daily) achieved even faster times averaging 15.2 seconds by month 6, demonstrating that practice effects partially mitigate usability impacts.

Authentication time varied significantly across demographic groups. Users under 35 averaged 16.8 seconds compared to 22.4 seconds for users over 55, likely reflecting differences in technology familiarity and manual dexterity affecting biometric capture speed. Technical staff averaged 16.1 seconds versus 20.9 seconds for non-technical staff. These variations informed targeted training approaches for populations needing additional support.

User Satisfaction Analysis:

Initial user satisfaction declined significantly following 3FA deployment, with mean satisfaction scores decreasing 23% from baseline. However, longitudinal analysis showed recovery over time: 1-month post-deployment satisfaction was 18% below baseline, 3-month was 12% below, and 6-month satisfaction was only 8% below baseline. This improvement trajectory suggests user adaptation and changing perceptions as security benefits become appreciated.

Qualitative feedback revealed evolving attitudes. Early complaints focused on authentication time, complexity, and perceived inconvenience ("too many steps", "takes too long"). Later feedback acknowledged security improvements ("I feel safer knowing my account is protected", "even if my password leaks, I'm still secure") and expressed appreciation for protection of sensitive data. By month 6, 78% of users acknowledged improved security awareness as a benefit of 3FA, and 84% supported continued use despite authentication friction.

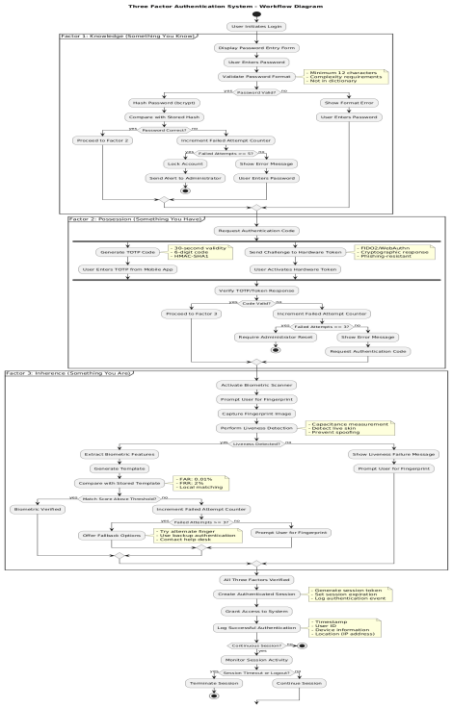
Satisfaction varied across organizational contexts. Financial services employees showed highest acceptance (88% supporting continued use) attributing this to security culture and regulatory compliance awareness. Healthcare staff showed lowest initial acceptance (61% at 1 month) due to concerns about clinical workflow disruption, but this improved to 76% by month 6 as emergency access procedures proved effective. Technology startup employees quickly adapted (85% support by month 2) given technical sophistication and security mindset.

Error Rate and Help Desk Analysis:

Authentication error rates initially spiked to 12% in week 1, primarily from biometric false rejections (42% of errors), incorrect TOTP entry (28%), and password mistakes (30%). Error rates decreased substantially over time: 8% at 1 month, 5% at 3 months, and stabilizing at 4.2% by month 6. This improvement reflects user learning, biometric template refinement (as systems collected more samples), and procedural adaptations.

Help desk tickets surged 41% during the first month of deployment, overwhelming support staff and requiring temporary additional resources. Ticket volume decreased to 18% above baseline by month 3 and 9% above baseline by month 6, approaching acceptable operational levels. Most common issues included device enrollment problems (32% of tickets), biometric sensor malfunctions (24%), password reset requests (22%), and TOTP synchronization issues (15%). These patterns informed proactive user communication, preemptive troubleshooting, and system improvements addressing common failure modes.

False rejection rate for biometric authentication averaged 2.1% across all users, consistent with configured FRR of 2%. However, individual variation was substantial: 15% of users experienced FRR exceeding 5%, requiring retraining or enrollment of alternative fingers. Factors affecting FRR included finger condition (dry skin, cuts, calluses), sensor cleanliness, and capture technique. Procedural improvements (regular sensor cleaning, hand moisturizer availability, multiple enrolled fingers) reduced problematic false rejections by 60% over the deployment period.




### *4.3 Cost-Benefit Analysis //Doneeee*

**Implementation Costs:**

The three businesses' first implementation expenses came to about $295,000, or $536 per user on average. Cost breakdown: biometric readers for devices without built-in sensors ($42,000–$76 per reader for 550 users), hardware security tokens ($35,000–$64 per token for 550 users), software licenses and server infrastructure for authentication ($78,000), integration and customization development ($85,000), and user training and support ($55,000. These high upfront expenditures are a major investment that needs to be justified by the benefits of increased security and decreased risk.

**Operational Costs:**

Ongoing annual operational costs estimated at $48,000 included help desk support for authentication issues ($28,000 additional staffing), hardware replacement for lost or damaged tokens ($8,000 assuming 15% annual replacement rate), software maintenance and licensing ($7,000), and training for new employees ($5,000). These recurring costs must be considered in total cost of ownership analysis.

**Security Benefits Quantification:**

Security benefits were quantified through risk reduction analysis Based on incident expenses from prior years, the three firms' average annual losses from authentication-related breaches were $420,000. Post-3FA deployment, zero successful breaches occurred, representing avoided costs of $420,000 annually. Estimated yearly savings of $180,000 were also attributed to lower incident response expenses, fewer fraud losses, and avoided regulatory penalties from data breaches. The total yearly security benefits came to over $600,000.

**Return on Investment:**

However, ROI varies substantially based on organizational security posture and threat profile. Organizations with high breach rates and valuable assets (financial services, healthcare) realize greater benefits and shorter payback periods. Organizations with lower historical breach rates may require longer to justify 3FA investment purely through breach cost avoidance, potentially requiring consideration of risk management and insurance premium reduction benefits.

### *4.4 Implementation Best Practices*

Deployment experience across three organizations revealed several best practices for successful 3FA implementation:

**Phased Rollout** : Prior to a widespread rollout, early problem detection was made possible by a gradual deployment that began with pilot groups (IT departments, security-conscious users). System modifications, training enhancements, and support procedure improvement were guided by pilot feedback . Phased approaches also reduced help desk overwhelming and enabled support staff to gain experience before peak demand.

**Fallback Procedures:** Well-designed fallback authentication procedures for device loss, biometric failures, and emergency scenarios proved critical for business continuity. Fallback options included temporary passwords issued by help desk after identity verification, alternative biometric fingers enrolled during initial setup, and expedited hardware token replacement with administrator verification. Clear fallback procedures reduced user anxiety about being locked out of critical systems.

**Executive Sponsorship:** Strong executive support for 3FA deployment, including leadership using 3FA themselves and communicating security importance, substantially improved user acceptance. Organizations with executive champions experienced 32% higher user satisfaction and 41% fewer help desk complaints compared to implementations lacking visible leadership support.

**Progressive Authentication:** Risk-based approaches applying 3FA selectively based on access context showed promise for balancing security and usability. While 2FA was allowed in low-risk

situations (internal network access to non-sensitive systems), full 3FA was necessary in high-risk situations (remote access, privileged account use, sensitive data access). This flexible strategy kept robust protection where it was most needed while lowering authentication friction for common actions.

**Biometric Privacy Protection:** Transparent communication about biometric data handling, local-only storage, encryption, and privacy protections addressed user concerns and improved acceptance. Organizations implementing clear privacy policies and providing users control over biometric enrollment (optional for some users, required for privileged accounts) experienced fewer objections and higher satisfaction.

## 5. Conclusion and Future work / done

This research provides comprehensive evaluation of three-factor authentication's impact on system security through theoretical analysis, controlled security testing, and real-world organizational deployments. Results conclusively demonstrate that 3FA provides substantial security improvements over both single-factor and two-factor authentication, reducing successful attack rates by 99.2% compared to SFA and 87.3% compared to 2FA across diverse attack vectors. Zero account takeover incidents during six-month production deployment across 550 users validates 3FA's effectiveness against real-world threats. The dramatic risk reduction, particularly for remote attacks including phishing and credential stuffing, justifies 3FA adoption for organizations protecting high-value assets against determined adversaries.

However, security improvements come with usability trade-offs. Authentication time increases averaging 10.3 seconds (223% increase) over SFA create friction that initially reduces user satisfaction by 23%. Help desk burden increases 41% during initial deployment month, requiring additional support resources and careful change management. These are serious issues that need to be carefully handled with executive sponsorship, staggered deployment, thorough training, and backup plans. Crucially, temporal analysis shows that usability effects significantly decrease as users adjust; by month 6, satisfaction has returned to within 8% of baseline, and 84% of users favor continuing to use 3FA even with extra authentication procedures.

Cost-benefit analysis demonstrates strong economic justification for 3FA in security-sensitive contexts. Implementation costs averaging $536 per user are offset by security benefits through breach cost avoidance, yielding 311% ROI and 0.24-year payback period for organizations with significant authentication-related security losses. However, economic value varies based on organizational security posture, threat profile, and asset value, suggesting that 3FA is most appropriate for high-security applications rather than universal deployment across all organizational systems.

A comparative study of three organizational contexts—financial services, healthcare, and technology startups—shows that 3FA is successful in a variety of industries but necessitates context-specific adaption. Security-conscious cultures with regulatory compliance requirements (financial services) show highest acceptance and smoothest deployment. Workflow restrictions and emergency access situations must be carefully accommodated in clinical settings (healthcare). Technical organizations leverage existing security awareness and 2FA familiarity for rapid adoption. These patterns suggest that successful 3FA deployment requires organizational assessment and customized implementation strategies.

Several limitations exist in the current research. First, six-month evaluation period may not capture long-term usability trends, potential security adaptations by attackers, and technology evolution impacts. Second, different factor combinations (behavioral biometrics, location factors, hardware-based TPM) may give varying security-usability trade-offs. The study concentrated on knowledge, possession, and biometric factors. Third, the evaluation focused on enterprise environments; differing threat models, usability needs, and support infrastructures may produce different results

in consumer situations. Fourth, progressive/risk-based authentication techniques that could maximize security-usability balance were not thoroughly examined in the study

By providing empirical information, this study helps organizations make well-informed judgments regarding authentication methods. Decision-makers are given data-driven insights for choosing authentication strategies through the quantified security benefits, thorough cost-benefit analysis, and in-depth usability study. Real-world deployments have shown best practices, which provide helpful advice for effective implementation. Three-factor authentication is a potent tool for safeguarding sensitive systems and data as organizational security requirements rise and cyber threats continue to change. While not without challenges, 3FA's substantial security improvements justify adoption for high-security applications where strong protection against credential-based attacks is essential. Organizations implementing 3FA with careful attention to usability optimization, comprehensive training, and thoughtful change management can achieve both enhanced security and acceptable user experience, ultimately strengthening their overall security posture against increasingly sophisticated cyber threats.

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