



A novel dual and triple shifted RSVP paradigm for P300 speller

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ABSTRACT

Background: A speller system enables disabled people, specifically those with spinal cord injuries, to visually select and spell characters. A problem of primary speller systems is that they are gaze shift dependent. To overcome this problem, a single Rapid Serial Visual Presentation (RSVP) paradigm was initially introduced in which characters are displayed one-by-one at the center of a screen.

New method: Two new protocols, Dual and Triple shifted RSVP paradigms, are introduced and compared against the single paradigm. In the Dual and Triple paradigms, two and three characters are displayed at the center of the screen simultaneously, holding the advantage of displaying the target character twice and three times respectively, compared to the one-time appearance in the single paradigm. To compare the named paradigms, three subjects participated in experiments using all three paradigms.

Results: Offline results demonstrate an average character detection accuracy of 97% for the single and double protocols, and 80% for the Triple paradigm. In addition, average ITR is calculated to be 5.45, 7.62 and 7.90 bit/min for the single, Dual and Triple paradigms respectively. Results identify the Dual RSVP paradigm as the most suitable approach that provides the best balance between ITR and character detection accuracy.

Comparison with existing methods: The novel speller system (the Dual paradigm) suggested in this paper demonstrates improved performance compared to existing methods, and overcomes the gaze dependency issue.

Conclusions: Overall, our novel method is a reliable alternative that both removes limitations for users suffering from impaired oculomotor control and improves performance.

1. Introduction

Brain computer interfaces (BCI) are communication systems that convert the brain's neural activities into functional commands for external devices (Acqualagna and Blankertz, 2013). BCI systems serve a variety of functions such as robot control (Bell et al., 2008), speller systems (Yin et al., 2013) etc. BCI systems are capable of creating direct communication channels to connect the human brain with computers. It can be said that the main purpose of BCI systems is to enable its users, especially those with injuries to or degenerative diseases of the central nervous system (producing severe speech and physical impairments), to communicate with the outside world using only their brain signals. According to this goal description, two main functions are expected from each BCI system; 1) to be able to detect neural activities and understand the purpose of the user and 2) to interpret and translate brain signals into understandable commands for an external device. Amongst the different methods of recording brain signals for use in BCI, Electroencephalography (EEG) is the most commonly used, due to its

advantages in providing higher temporal resolution, non-invasiveness, cost efficiency and transportability (Orhan et al., 2012).

Depending on the diverse types of components of EEG signals, (in addition to event-related desynchronization (ERD) or event-related synchronization (ERS)) BCI systems can be divided into steady state visually evoked potentials (SSVEP)-based (Chen et al., 2017) and event-related potentials (ERP)-based (Zhang et al., 2012) systems, the latter being our area of focus in this paper. Event-related potentials are the brain's response to an external stimulus or event. ERPs have various components, each of which contains specific information regarding the type of ERP (Sur and Sinha, 2009). One of the most common ERP-based BCI systems is the speller system. Speller systems use an intelligent approach to evoke a specific ERP component, which in most systems is based on the p300 component (Lin et al., 2018). The p300 component has a positive potential that appears with a 300–500 ms delay after the onset of the target stimulus. The p300 component is evoked in an Oddball paradigm when a target stimulus appears among a string of non-target stimuli. This component is usually more evidently visible in

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central electrodes (C, Fz, Pz) compared to other electrodes (Gonzalez and Polich, 2002; Elshout, 2009).

The first ERP-based speller system was introduced by Farwell and Donchin, known as the matrix speller (Farwell and Donchin, 1988). In this protocol, 36 characters, consisting of the letters of the alphabet and single-digit numbers are organized in a 6×6 matrix. In this matrix, the rows and columns are illuminated one by one and randomly, and the user must focus on one of the symbols which is the target-character. The p300 component is expected to be evoked in the subject's brain signal when the row or column of the target-character is illuminated. By performing numerous repetitions of this experiment and averaging over the target stimuli, the p300 component will be easily observable. The target-character can then be identified by determining the row and column of the evoked p300 component (Farwell and Donchin, 1988).

Although Farwell and Donchin's protocol was the first paradigm presented for speller systems and was widely used, however, recent studies have shown that target character selection in this paradigm is dependent on eye movement, also referred to as "gaze dependent" (Acqualagna et al., 2010). Therefore, this protocol is not suitable for users suffering from impaired oculomotor control. Many studies have been conducted to identify solutions for creating gaze independent speller matrices, which ultimately led to two solutions; 1) changing the type of modality and substituting vision with touch (Höhne et al., 2011) or audio (Brouwer and Van Erp, 2010), and 2) changing the movement paradigm. Hex-O-Spell and Rapid Serial Visual Presentation (RSVP) paradigms, and more recently miniature asymmetric visual evoked potentials (aVEPs) have been suggested in this regard. Miniature-event-related potentials were proposed by Xu et al. (2018) to overcome the problem of visual fatigue caused by large visual stimuli in traditional BCIs. Their experiment results on the use of miniature visual stimuli for speller BCI systems demonstrated initial feasibility for this method. However, the method elicited weak EEG features, suggesting further work and experimentation is still required for the better implementation of this novel approach. In the Hex-O-Spell paradigm, characters are divided into six groups, and each group is placed on one edge of a hexagon. This protocol uses a two-step process for target character selection. As the first step, each of the six groups are illuminated one by one and at random, and the subject must focus on the group containing the target character once it is illuminated. This group of characters will be selected as the target group. Then, the characters within the selected target group are placed around a hexagon (one character at each edge) and randomly illuminated, where the target-character can be determined (Treder and Blankertz, 2010).

In the RSVP paradigm, characters are randomly displayed one by one at a fast rate on the center of the screen. Target character selection in this method is not gaze dependent (Orhan et al., 2012; Acqualagna et al., 2010; Mijani et al., 2018). Further changes were applied to the primary RSVP protocol (single RSVP) in order to increase accuracy by performing actions that help better distinguish characters, such substituting upper case letters with lower case and using colored characters (Acqualagna and Blankertz, 2013, 2011). Although the RSVP paradigm is considered a new protocol in speller systems and overcomes the gaze dependency issue of the matrix speller, however, displaying only one character at each time slot elongates the experiment duration, which exhausts the user and decreases Information Transfer Rate (ITR). In order to address this time efficiency issue which is present in the single RSVP paradigm, shifted Dual and Triple RSVP paradigms are introduced and utilized in this study. To better understand the concept of these two paradigms, another use of the RSVP paradigm (other than speller systems) named "RSVP Image Search" shall be presented. In this paradigm, the goal is to identify the target image from a string of images (Sajda et al., 2003; Huang et al., 2011; Yu et al., 2012; Mohedano et al., 2015). To decrease experiment length and increase ITR in RSVP image search paradigms, Dual and Triple RSVP image search paradigms have been introduced. In the Dual RSVP paradigm presented by Cecotti (2016), unlike the single paradigm where one

image is displayed at a time, two images appear simultaneously at the center of the screen. In this paradigm, the same string of images on the left also appear on the right side, but with a certain delay. For each of the images that are to be detected, the user must first gaze at the string of images on the left until the target image appears, and then focus on the string of images on the right until once again observing the target image. To detect the next image target image, the user must once again focus on the left string of images, and this loop continues until all images are observed. A similar approach is followed for Triple RSVP paradigms, as further discussed in this paper (Lin et al., 2017).

The use of Triple RSVP paradigms for speller systems has been previously studied by Lin et al. (2018). Using the underlying concepts of the published method and applying some fundamental changes, we hereby introduce a shifted RSVP paradigm that we believe holds multiple advantages over the previously published method. In the Triple paradigm proposed by Lin et al. (2018), three characters are shown to the subject concurrently and the subject is asked to focus on all three at the same time and try to detect the target character. In other words, their method splits the 36 characters into 12 sets of images each containing 3 characters. These 12 groups of characters are then shown to the subject as stimuli, and the subject must identify the target character from the three existing characters. In our novel shifted approach, although three characters are shown concurrently (for the Triple paradigm), but the characters are shown in strings and in a way that the subject only needs to focus on one character and can detect the target character with much more ease. The primary idea behind our method is storing the 36 characters in a string, and then creating a second and third string by only shifting (linear shift) the characters. Since the strings are linearly shifted, the user can anticipate which string will be showing the target character next. By doing so, we can now simultaneously display all three strings on the screen in a more organized manner to help the user focus on the characters easier, also allowing one stimulus per character (discussed in more detail in section 2.3). Hence, we create three P300s in each repetition compared to the one P300 created in the method proposed by Lin et al. (2018). Therefore not only is our method expected to yield higher accuracy and result in less characters being missed by the user, but it also allows 9 target characters to be detected with 3 repetitions, compared to the 3 target characters detected by Lin et al. (2018) in the same number of repetitions. Another advantage of our method is that it results in less visual fatigue since we require fewer repetitions for target character detection, which touches on the goal attempted by aVEPs. Therefore, the purpose of this study is to explore the extension of the described shifted Dual and Triple paradigms (Shifted Multi RSVP) presented for image search to speller systems and compare their performance against the single RSVP keyboard paradigm. It is expected that the Shifted Dual and Triple RSVP paradigms will improve ITR and reduce experiment duration while maintaining gaze independency.

2. Methods

2.1. Participants

Three male subjects within the age range of 25–28 and no previous training in this or any similar experiments participated in this experiment (mean = 25.5, SD = 1.5). Each participant was asked to take part in 3 experiments (one experiment for each paradigm). Subjects passed general medical examinations before participating in the experiments, and showed no symptoms of color blindness, neurological disorders or eye injury. The protocol of these experiments was approved by Iran's Medical Sciences ethics committee. All participants voluntarily took part in these experiments, and data was recorded in The National Brain Mapping Lab.

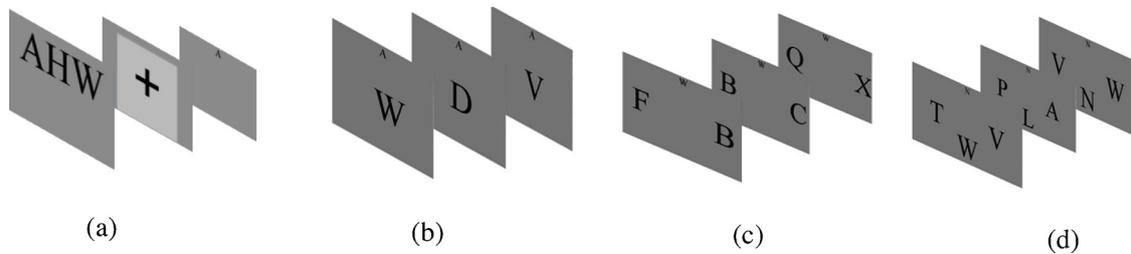


Fig. 1. a) Subject preparation, b) Single RSVP paradigm: displaying one character at a time, c) Dual RSVP paradigm: displaying two characters simultaneously in each stimulus, d) Triple RSVP paradigm: displaying three characters simultaneously.

2.2. Apparatus

EEG signals were recorded using a g.Hlamp (G. Tech Company) device. A total of 32 active electrodes were used in our experiments in accordance with the international “10-20” system, and all electrodes were referenced to the right ear. The signal sampling rate was 512 Hz and a digital notch filter was activated at 50 Hz. Stimulation protocols were designed using Psychtoolbox and displayed on a 19.5 inch LED with a resolution of 1366×768 and refresh rate of 60 Hz. For all experiments, the subject was placed at an eye distance of 90 cm away from the monitor, and the horizontal and vertical distance between each two characters on the monitor was 14 and 5 cm, respectively. This resulted in horizontal and vertical visual angles of 4.44 and 1.54 degrees, respectively.

2.3. Experiment design and procedure

In this study, single, Dual and Triple RSVP Keyboard paradigms have been designed and experimented on. In all three paradigms, symbols are displayed in black within a grey background. As displayed in Fig. 1a, to better prepare the subject, the target word appears at the top of the screen for 1 s before the start of each run. Next, the fixation cross appears and vanishes after 1 s, followed by the target character being displayed for 1 s, and finally the stimuli start to appear one after the other (all these steps occur in offline phase).

In the single RSVP paradigm, characters are displayed one at a time at the center of the screen, as demonstrated in Fig. 1b. In the Dual RSVP paradigm, two characters are displayed at each time frame, as depicted in Fig. 1c. In other words, two strings are displayed in parallel, where the second string is the delayed version of the first. To create the string and its delayed version, 26 alphabet characters are considered as the primary string. The second string is created by applying a circular shift of 4 units to the first string. An example of two strings created in such a way would look similar to what is demonstrated below. In the Triple RSVP paradigm, three characters are displayed at each time slot, as depicted in Fig. 1d.

String 1:

V P R F J E C S Q T D M O U A Z Y N I H L K G W B X

Shifted string 1:

G W B X V P R F J E C S Q T D M O U A Z Y N I H L K

In the Dual RSVP paradigm, the subject is asked to first gaze at the string of characters on the left until the target character appears, then focus on the string of characters on the right. After observing the target character, the user is once again asked to focus on the left string of characters (as demonstrated in Fig. 2.a). In the Triple RSVP paradigm the goal is to display the target character three times in each repetition, doing so by using three parallel character strings. A similar order applies to the Triple RSVP paradigm, but in this case, after the target character is observed in the right string, the user is asked to gaze at the bottom string. After the appearance of the target character in the bottom string, the user must once again shift attention on the left string. This requires multiple attention shifts between the different strings, creating the possibility of missing the target stimulation while shifting

focus from one string to the other in the Dual and Triple paradigms (if the strings are parallel with circular shift). For example, if “G” is the target character, after seeing “G” in the left string, the subject will not be able to see the character “G” in the right string. To overcome this problem, the circular shift is replaced with a linear shift, and the three symbols “!”, “.” and “?” are also added to the string. Ultimately, the Dual paradigm contains 29 characters consisting of 26 alphabet letters and three punctuation symbols. A sample string and its delayed version would therefore look similar to this:

String 1:

UNMRWHYVCKTBZOFLEAJIPXDQG!?

Shifted String 1:

!?.UNMRWHYVCKTBZOFLEAJIPXDQG

To address this issue in the Triple RSVP paradigm, a primary string is created and the second and third strings are created using determined delays. Once again in order to prevent the loss of target character detection, linear delays of 3 and 6 units are applied to the second and third strings, respectively. In addition, digits 1–9 are also added to the stimulus characters. Another important factor that must be taken into account in the design of Dual and Triple RSVP paradigms is that no two characters should be repeated together more than once. For example, if “QX” characters appear together, they must not re-appear together in any of the next iterations. Character strings used in the Dual and Triple RSVP paradigms along with their delayed versions are presented in Tables 1 and 2. A sample Triple RSVP paradigm character string and its delayed versions can be observed below:

String:

UNMRWHYVCKTBZOFLEAJIPXDQG123456789

1st shifted string:

456UNMRWHYVCKTBZOFLEAJIPXDQG321789

2nd shifted string:

987123UNMRWHYVCKTBZOFLEAJIPXDQG645

By using the aforementioned technique to avoid missing target characters, we will have different numbers of characters and different stimulus times for each of the three paradigms. In the single paradigm, 26 characters comprised of letters of the alphabet are used as stimulations. These stimulations are randomly displayed 10 times with stimulus time of 187.5 ms (5.33 Hz). Therefore, the time required to spell each character is equal to $187.5 \times 10 \times 26 = 48,750$ ms (48.75 s). In the Dual paradigm, the display of each character is repeated 5 times with a stimulus duration of 250 ms (4 Hz). In this paradigm, the delay of the second string is equal to 750 ms. The time required for character detection in this paradigm is $250 \times 29 \times 5 = 36,250$ ms (36.25 s). In the Triple paradigm, each character is displayed 3 times with a stimulation time of 250 ms (4 Hz). In this paradigm, the delay of the second and third strings are 750 ms and 1500 ms, respectively. The time required to type each character is therefore $250 \times 35 \times 3 = 26,250$ ms (26.25 s). From these calculations, it can be observed that the Dual and Triple paradigms can significantly decrease the time required for character detection.

In the experiments related to each of the protocols in offline mode, subjects are asked to spell 45 characters. Subjects are seated approximately 90 cm from the monitor on a comfortable chair, and are asked to

String 1:
V P R F J E C S Q T D M O U A Z Y N I H L K G W B X
Shifted string 1:
G W B X V P R F J E C S Q T D M O U A Z Y N I H L K

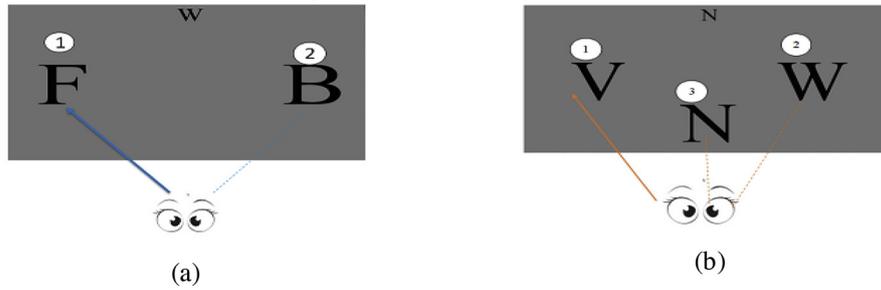


Fig. 2. a) Experiment procedure in the Dual RSVP paradigm: the subject is first asked to focus on the left string, and after seeing the target character, shift focus to the right and once again left after character detection, b) Experiment procedure in the Triple RSVP paradigm: the procedure is similar the Dual paradigm, with the addition of third string.

Table 1
Five character strings and their delayed versions in the Dual paradigm.

String1	UNMRWHYVCKTBZOFLEAJIPXDGG!..?
First Shifted String 1	!..?UNMRWHYVCKTBZOFLEAJIPXDGG
String2	SOHWQKAIYCXPGMBDEFTZULVJRN!..?
First Shifted String 2	!..?SOHWQKAIYCXPGMBDEFTZULVJRN
String3	VPRFJECSTDMOUAZYNHILKGWBX!..?
First Shifted String 3	!..?VPRFJECSTDMOUAZYNHILKGWBX
String4	HDBNWETLMKOPVZFSCAJGRUQYIX!..?
First Shifted String 4	!..?HDBNWETLMKOPVZFSCAJGRUQYIX
String5	TJPHCIKFUXDMVOLSEBWAYZGQNR!..?
First Shifted String 5	!..?TJPHCIKFUXDMVOLSEBWAYZGQNR

Table 2
Three character strings and their delayed versions in the Triple paradigm.

String1	UNMRWHYVCKTBZOFLEAJIPXDGGQ123456789
First Shifted String 1	456UNMRWHYVCKTBZOFLEAJIPXDGGQ321789
Second Shifted String 1	987123UNMRWHYVCKTBZOFLEAJIPXDGGQ645
String2	SOHWQKAIYCXPGMBDEFTZULVJRN123456789
First Shifted String 2	789SOHWQKAIYCXPGMBDEFTZULVJRN564231
Second Shifted String 2	321654SOHWQKAIYCXPGMBDEFTZULVJRN798
String3	VPRFJECSTDMOUAZYNHILKGWBX987654321
First Shifted String 3	312VPRFJECSTDMOUAZYNHILKGWBX695847
Second Shifted String 3	968574VPRFJECSTDMOUAZYNHILKGWBX132

also keep count of the number of times they view the target character. For each protocol, the experiments are performed in a single session and in multiple runs. Each run is comprised of spelling 3 characters, and the subject is given a few minutes of resting time between the runs.

2.4. Data analysis

For the purpose of data analysis, all channels were first filtered using a digital band-pass filter in the range of 0.5–30 Hz, and then down-sampled at 128 Hz. EEG signals were divided into epochs in the range of 0 to 800 ms after the onset of the stimulation. It must be noted that 800 ms is the difference between t1 and t2, and the EEG recording itself is not stopped at 800 ms. The mean of 0–100 ms before each stimulation was also deducted from the corresponding epoch for baseline correction. Since the range of recorded EEG signals are approximately between -50 to +50 μV, epochs with a max-min range exceeding 100 μV were considered artifacts and the entire epoch was removed from the signal in order to remove movement artifacts such as eye movement.

In order to classify target characters from non-target characters, most previous studies have extracted and used temporal features. In addition to temporal samples, wavelet coefficients were also used as features in this study. Amongst the possible features, wavelet transform is one of the most effective for distinguishing between target and non-target stimulations in ERP analysis. To compute the coefficients of

wavelet transform, five-octave discrete wavelet transform is applied to each epoch with the mother wavelet “bior 2.2” (Tahmasebzadeh et al., 2013). By applying this wavelet transform, the signal is decomposed into coarse detail and coarse approximation. Wavelet coefficients can be obtained by placing approximation coefficients from the last stage and detail coefficients from different stages together (further explained in (Tahmasebzadeh et al., 2013)). Fig. 3 demonstrates the average wavelet coefficients for target and non-target stimuli across different trials. As it can be observed, most of p300’s energy in terms of wavelets is amongst a limited number of samples, and these samples demonstrate the most distinction between target and non-target signals. Therefore, only the initial wavelet coefficients (first 50) are used. Temporal samples and retained wavelet coefficients are then placed together to form the feature vector.

Amongst the different available channels, we have used channels F3, Fz, F4, Fc1, Fc2, Cz, Cp1, Cp2, P3, Pz and P4 in our experiments. The selection of these channels was based on two factors, the first being that most similar studies have used the same channels for detecting p300 (Kaper et al., 2004; Rakotomamonjy and Guigue, 2008; Liu et al., 2013). The second reason is that these channels show a stronger p300 on our data compared to the other channels. If we gather the time samples and wavelet coefficients extracted from each epoch using the aforementioned 11 channels, we obtain a 1400-dimension feature vector. Because the dimension of this feature vector is too large, using a dimension reduction method is critical. The Lasso method (Tibshirani, 2011) is applied and the dimension is reduced to approximately 200 to 250 features.

To detect the target character from non-target characters in each experiment, classification is performed using linear RLDA (Acqualagna and Blankertz, 2011) and non-linear SVM (Rakotomamonjy and Guigue, 2008) classifiers. Classification is performed separately using

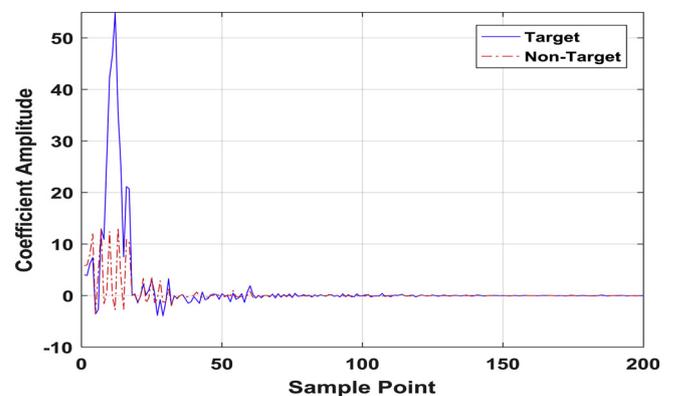


Fig. 3. Wavelet transform coefficients obtained using a 5-step discrete wavelet transform. The red curve is the average of target signal coefficients and the blue curve is for the average of non-target signals.

each of the named methods and the final results are compared. In our classification method, we use scores instead of class labels to help with target character detection. As previously mentioned, in the Dual RSVP paradigm, two characters are displayed simultaneously in each stimulus. The fact that each stimulus contains two characters at each time frame makes target character identification a complicated issue. Dedicating a score to each of the two characters in every stimulus helps address this issue. Since no two characters will re-appear together, by averaging each character's score in different appearances, the maximum score determines the target character. It is better to explain the scoring system with an example. Let us say for example that the characters "AB" appear together in a stimulus where "B" is the target character. Theoretically, the score for this stimulus would be 0.9, whereas other stimuli would have a score in the range of 0.1 to 0.2. We pertain this score to both characters "A" and "B". The challenge now becomes determining which of these two characters are the target character. Since no two characters will re-appear together, we may assume that the next stimuli containing each of these characters would be a different combination of characters, let us assume "BF" and "AX". In these repetitions, the score of the "BF" stimulus would be approximately 0.9, where as that of "AX" would be 0.2. Therefore, for two repetitions of "B" we obtain scores of 0.8 and 0.9, where as those scores would be 0.2 and 0.9 for "A". By averaging the scores of each character over different repetitions, the score for "B" would be 0.75, whereas the score for "A" would be 0.3, indicating character "B" is the target stimulus. The same approach is used for target character detection in the Triple RSVP paradigm.

2.5. Algorithm performance evaluation

The performance of the RSVP-based speller is quantified using ITR and character detection accuracy. In order to accurately estimate classification accuracy, four-fold cross-validation is used. ITR is calculated using the relation below:

$$ITR = [\log_2(N) + p \log_2(p) + (1 - p) \log_2(\frac{1-p}{N-1})] \times \frac{60}{T}$$

In the above equation, p is character detection accuracy, N is the number of classes and T demonstrates the time required to spell one character (in terms of seconds).

3. Results

3.1. ERP analysis

Grand average ERPs for the three protocols on one of the subjects is illustrated in Fig. 4. In each figure, the blue curve is the ERP response to target stimulus and the red curve is the ERP response to non-target stimulus on the Pz electrode. In Fig. 4.a, the wave of the p300 component can be observed for the single RSVP paradigm. Fig. 4.b demonstrates the ERP waves induced by the Dual protocol. As previously mentioned, target stimulus is displayed twice in each repetition in the Dual paradigm, therefore two p300 components are evoked. The red lines marked in Fig. 4.b demonstrate the moment of appearance of the target stimulation in the left (0 ms) and right (750 ms) strings. The ERP wave form produced by the Triple paradigm is also demonstrated in Fig. 4.c. In this case, three distinct p300 components are evoked. From these wave forms, it can be concluded that the Dual and Triple paradigms are effective in evoking the p300 component.

3.2. Classification

For classification in offline mode, non-linear ensemble SVM and LDA with covariance shrinkage matrix were used. Character detection accuracy and ITR obtained using these classifiers for the different protocols and all three subjects are reported in Table 3. For training the

ensemble SVM classifier, three SVM classifiers with Gaussian kernels have been designed, and classifier parameters (c, σ) have been optimized through trial and error. Classification results demonstrate a mean character detection accuracy of 0.97 for the single, 0.97 for the Dual and 0.80 for the Triple paradigms. The ITR for these three protocols is also reported as 5.45, 7.62 and 7.9 bit/min, respectively. The curves for ITR and character detection accuracy for the three subjects have been plotted as a function of different repetitions in Fig. 6. In these curves, a relatively inverse relationship can be observed between the accuracy rate and ITR. Other than the first iterations, a monotonic decrease in ITR is observed with repetition increase (Fig. 6b, 6d and 6f), while accuracy increases.

3.3. Comparison with existing methods

The results of our proposed shifted paradigm are compared to previously published non-shifted paradigms in single, dual and triple paradigm modes in Table 4. The methodology of the single mode is the same for all experiments in Table 4, and differences in accuracy and ITR are defined by the device type and character display time, respectively. Throughout the three modes, our method consistently produces a lower ITR because character display time has been selected to be longer than other methods, and since this is consistent across all modes, it demonstrates that it is not a flaw of our shifted paradigm, rather a design preference. Note that in the dual mode, when compared to Mijani et al. (2018), our method demonstrates significantly higher accuracy, while producing almost the same ITR. In the triple mode, our method demonstrates higher accuracy compared to Lin et al. (2018) and Mijani et al. (2018) however has a notably less ITR compared to both. Apart from longer display time, reduction in ITR is also due to the nature of our shifted approach. We have aimed to minimize target-character miss rates by using a linear shift, which has led to our method holding the major advantage of having a target-character miss rate of zero, compared to the notable number of target-character misses observed when simulating the non-shifted methods.

4. Discussion

4.1. Results analysis

After obtaining the results from our experiments, we aim to compare the three protocols in terms of character detection accuracy and ITR. Average ITR for the single, Dual and Triple RSVP paradigms is observed to be 5.45, 7.62, and 7.90, with a mean character detection accuracy of 0.97, 0.97 and 0.80, respectively. As it can be observed, although the average character detection accuracy is higher in the single protocol compared to the triple, however, average ITR in the Triple protocol is much higher.

As mentioned, in the single paradigm the target character appears once in each repetition, so with 10 repetitions, the target character appears 10 times. In the Dual paradigm the target character appears twice in each repetition, and therefore it appears 10 times in 5 repetitions. In the Triple paradigm, the target character appears 9 times in 3 repetitions, as it appears 3 times in each repetition. Since in the single, Dual and Triple paradigms, 10, 10 and 9 p300 components are evoked respectively, it was expected that the Dual and Triple paradigms show a much better ITR while maintaining accuracy. However, the results demonstrate that the high character detection accuracy of the single paradigm is sustained in the Dual paradigm but has decreased in the Triple paradigm. The increasing trend in ITR has however fulfilled the expectations, as ITR in the Triple paradigm increases significantly compared to the single paradigm. Yet, the significant advantage of the Triple paradigm is that the time it requires for 9 p300 component stimulations is almost half of the single paradigm (for 10 p300 component stimulations).

Another conclusion that can be made by comparing the results of

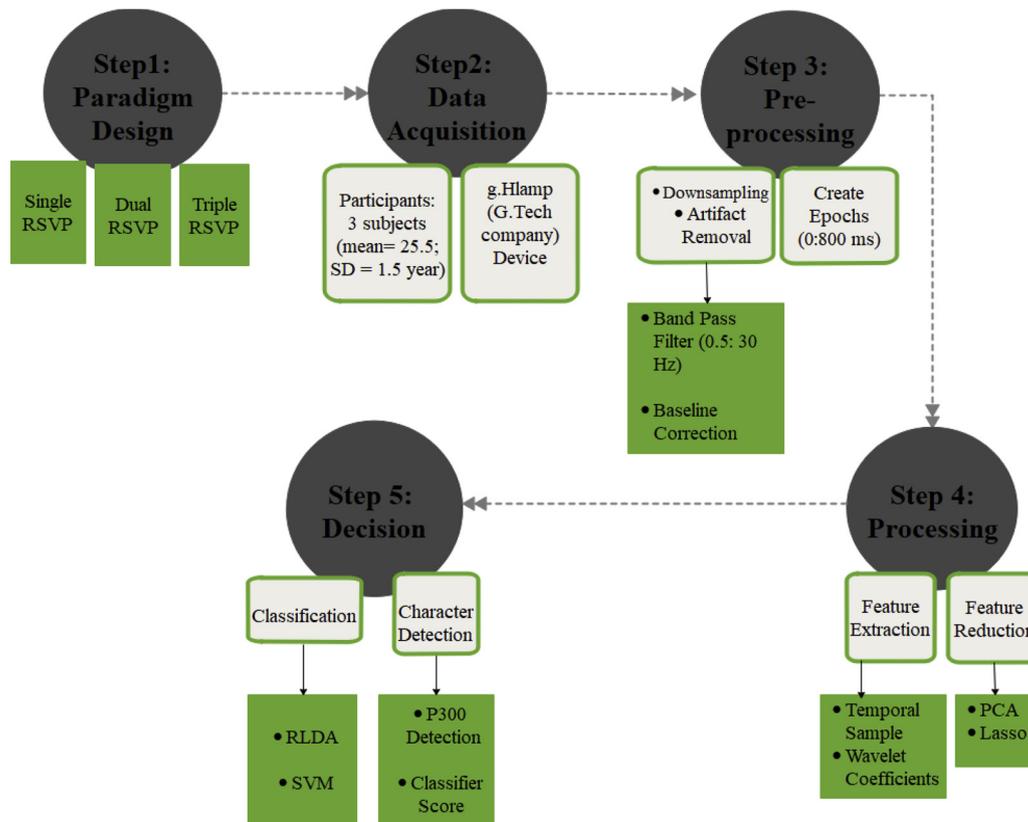


Fig. 4. Experiment procedure flow chart.

the three protocols is that in the Dual paradigm, in addition to maintaining accuracy, ITR increases significantly compared to the single paradigm. The Triple paradigm however results in a significant accuracy drop compared to the Dual paradigm, while not increasing ITR by a significant amount. Therefore, by considering these results, the Dual paradigm can be introduced as the most successful. Additionally, one may suspect that the Dual and Triple paradigms may increase the likelihood of missing the target more often than the single paradigm. In our experiments, a total of 6525 and 4725 samples were tested and collected for the dual and triple paradigms respectively, where not a single target character miss was recorded. This is because stimulus is repeated 5 and 3 times for the Dual and Triple characters respectively, therefore even if one miss occurs, since we averaged over the 3 or 5 repeats, it would have been compensated.

4.2. Paradigms analysis and comparison

In BCI systems and especially speller systems, a trade-off exists between character detection accuracy and ITR. As character detection accuracy increases with more repetitions, ITR decreases, and vice versa

Table 3 Character detection accuracy (%) and ITR (bit/min) resulting from the classification of the three protocols.

Classifier	Ensemble SVM						RLDA					
	Single RSVP		Dual RSVP		Triple RSVP		Single RSVP		Dual RSVP		Triple RSVP	
Results	ACC	ITR	ACC	ITR	ACC	ITR	ACC	ITR	ACC	ITR	ACC	ITR
Sub1	0.95	5.14	0.97	7.60	0.77	7.38	0.93	4.96	0.91	6.61	0.64	5.74
Sub2	0.97	5.46	0.95	7.24	0.75	7.04	0.95	5.14	0.97	7.60	0.77	7.38
Sub3	1.00	5.76	1.00	8.04	0.88	9.28	0.97	5.37	1.00	8.04	0.88	9.28
Mean	0.97	5.45	0.97	7.62	0.80	7.90	0.95	5.15	0.96	7.41	0.76	7.46
S.D	0.02	0.31	0.02	0.40	0.07	1.20	0.02	0.20	0.05	0.73	0.12	1.77

Table 4 Comparison of our proposed shifted paradigm with previously published non-shifted paradigms in single, dual and triple paradigm modes (where available). Note that for Lin et al. (2018) and Acqualagna and Blankertz (2013), experimental results were only reported for the triple and single paradigms respectively, hence limiting our comparison to these modes.

Mode	Paradigm	Accuracy (%)	ITR (bit/min)
Single	Single RSVP (Acqualagna and Blankertz, 2013)	94.8	7.0
	Single RSVP (Mijani et al., 2018)	78.74	3.65
	Single RSVP	97.0	5.5
Dual	Non-shifted RSVP (Mijani et al., 2018)	63.4	7.7
	Shifted RSVP	97.0	7.6
Triple	Non-shifted RSVP (Lin et al., 2018)	78.0	19.9
	Non-shifted RSVP (Mijani et al., 2018)	64.7	11.6
	Shifted RSVP	80.0	7.9

(as results from the Single Dual and Triple paradigms indicate). Therefore, depending on which of these parameters is of more importance for the purpose of a specific experiment, the other must be

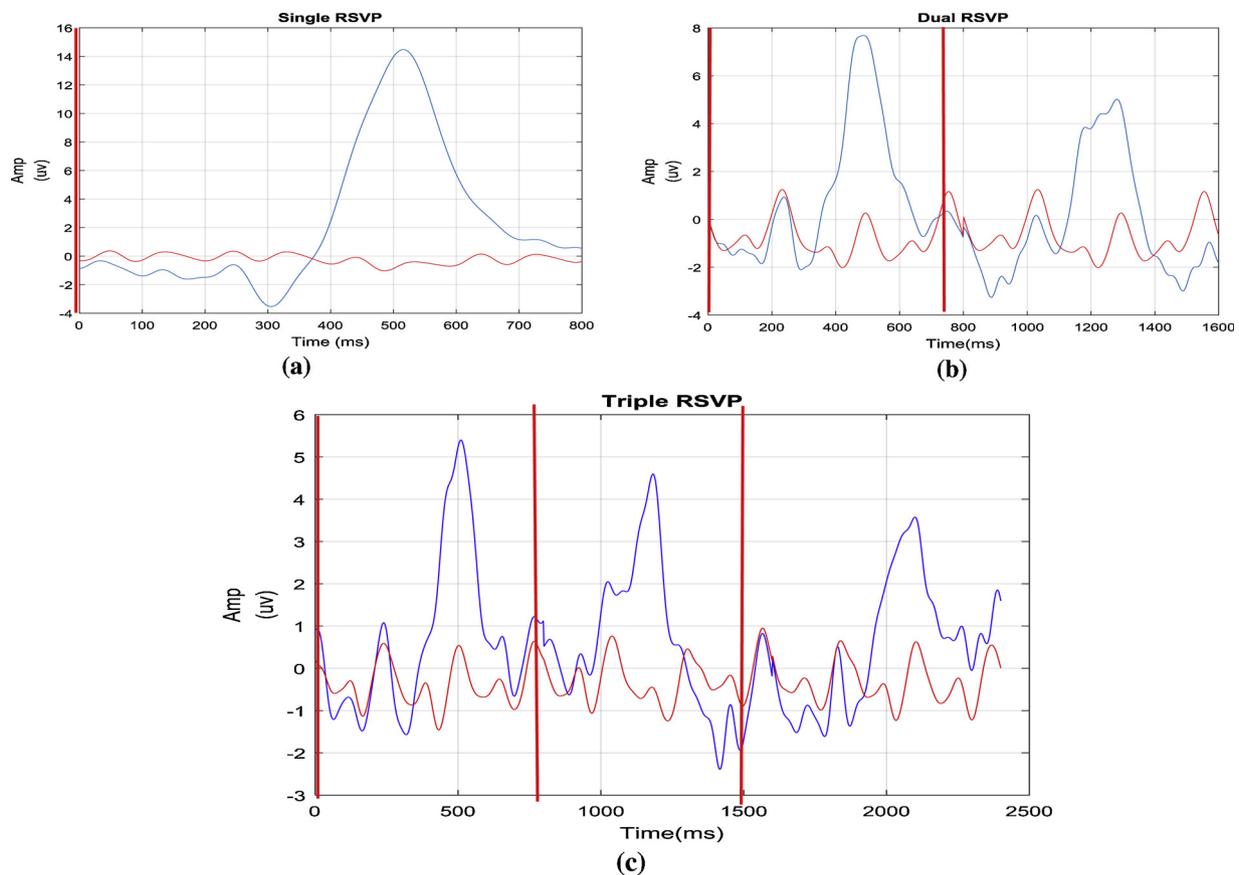


Fig. 5. Target and non-target ERP component curves for the three protocols; a) single b) Dual and c) Triple RSVP. In each plot, the blue and red curves correspond to target and non-target p300 component detection, respectively.

sacrificed for the improvement of that parameter.

An issue with the Dual and Triple paradigms is that after being displayed in the left string, the target character is re-displayed in the right (and also bottom for the Triple paradigm) string after 3 (and 6 for the bottom string) characters. Since the users are asked to shift focus on the next strings after viewing the target character in the left string, and the delay between the two strings is only 3 characters, the subject will see the target character immediately after shifting focus to the next string. After a few repetitions, this trend in target character appearance in the other two strings will become discoverable. This predictability may affect the Oddball nature of the experiment. Considering the results reported in Table 3, we may claim that the observed decrease in the p300's amplitude in the Dual and Triple paradigms does not disrupt the accuracy of the system and these paradigms are still effective. As depicted in the ERP curves for the Dual (Fig. 5b) and Triple (Fig. 5c) paradigms, the amplitude of the p300 component in the second and third strings must be smaller than the amplitude of the p300 component in the first string. We may also extend the findings from these experiments to a quadruple RSVP paradigm. In this protocol, 4 characters would be displayed at the center of the screen simultaneously. Although this protocol will decrease the experiment time, however, the fourth p300 component amplitude will most likely undergo a significant decrease, and despite adding complexity to this protocol, it will probably not increase the system's accuracy.

4.3. Contributions and limitations

Overcoming the gaze dependency problem in the previous speller matrices was the main motivation which led to the development of the primary RSVP paradigm. In this study, we have extended this approach and presented shifted Dual and Triple paradigms to improve character

detection accuracy and ITR compared to existing methods while maintaining gaze independency. Although in the Dual and Triple paradigms the user is asked to change focus between 2 or 3 different characters, but since the characters are placed close to each other and at the center of the screen, target character detection in these paradigms is not gaze dependent. By significantly reducing the visual angle to 1.54 degrees (discussed in section 2.1) compared to the previously reported value of 20 degrees (Cecotti, 2016) in the Dual paradigm, our approach can be beneficial to users with eye gaze limitations. Through gathering feedback from the users after each experiment, it was found that the Dual and Triple paradigms hold an advantage in terms of user comfort in focusing on the stimuli and character detection compared to the single paradigm. Since the rate of stimulus display in the single paradigm is much faster compared to the Dual and Triple paradigms, all users believed looking at the stimuli in the single paradigm required higher focus and thus their eyes felt more exhausted.

A major limitation of this study was that we were only able to recruit 3 male subjects for our experiments due to funding limitations. We acknowledge that this number of participants is too few and too specific (considering they were all young male students) to draw significant conclusions from, and we hope our work serves as a basis for more comprehensive studies with increased number of participants and a more diverse population in the future. Another limitation in our study is that all our subjects have a very high AUC to start with. It would be beneficial to test this method on subjects with lower starting AUCs to see if the results vary. Additionally, future work must recognize the fact that not all patients may have sufficient cognitive skills to accurately switch their attention between the letter streams after the target letter appears, and experimentation on such cases would be of interest. Lastly, it may be argued that decreasing attention to the letters in the Dual and Triple RSVP paradigms decreases signal to noise ratios. This raises the

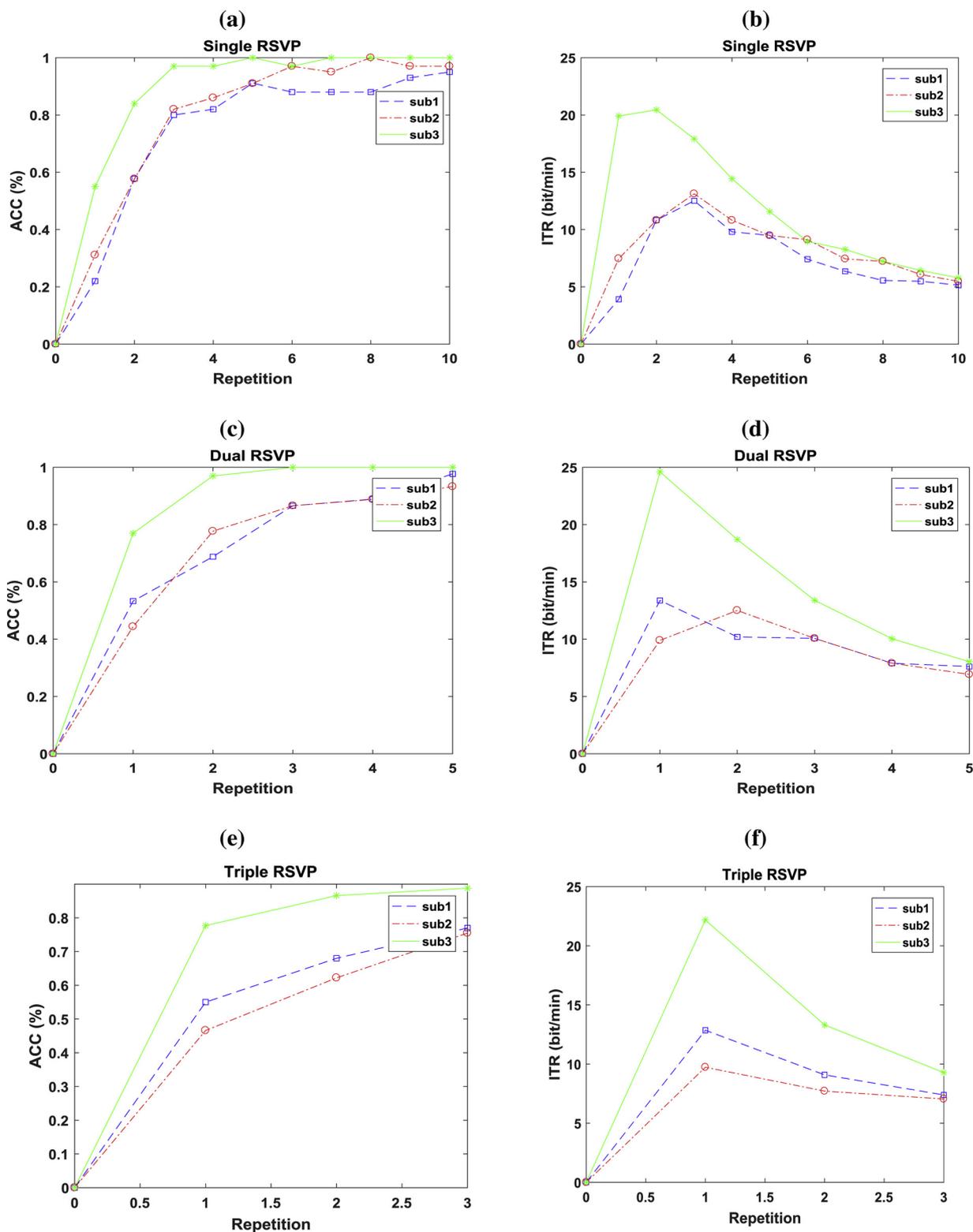


Fig. 6. Character detection accuracy and ITR as a function of number of repetitions in the single (a, b), Dual (c, d) and Triple (e, f) paradigms.

concern that at some baseline level of performance the use of Dual and Triple RSVP may decrease performance and ITR, which is a claim that requires further experimentation to approve or reject.

5. Conclusion

In this study, by comparing the results of the single and shifted Dual

and Triple RSVP paradigms, we aimed to determine the best approach in terms of ITR and character detection accuracy. By conducting some experiments, we obtained an average character detection accuracy of 97% for the single and double protocols, and 80% for the triple paradigm. In addition, average ITR was calculated to be 5.45, 7.62 and 7.90 bit/min for the single, Dual and Triple paradigms respectively. Results demonstrated equally good character detection accuracy for the single

and Dual paradigms, and a significant increase in ITR in the Dual paradigm compared to the single. The Triple RSVP paradigm demonstrates an almost equal ITR to that of the Dual paradigm, while decreasing character detection accuracy significantly. Therefore, the Dual paradigm can be introduced as the most suitable approach.

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