Enhanced Verbal Statistical Learning in Glossolalia

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Abstract

Glossolalia ("speaking in tongues") is a rhythmic utterance of word-like strings of sounds, regularly occurring in religious mass gatherings or various forms of private religious practices (e.g., prayer and meditation). Although specific verbal learning capacities may characterize glossolalists, empirical evidence is lacking. We administered three statistical learning tasks (artificial grammar, phoneme sequence, and visual-response sequence) to 30 glossolalists and 30 matched control volunteers. In artificial grammar, participants decide whether pseudowords and sentences follow previously acquired implicit rules or not. In sequence learning, they gradually draw out rules from repeating regularities in sequences of speech sounds or motor responses. Results revealed enhanced artificial grammar and phoneme sequence learning performances in glossolalists compared to control volunteers. There were significant positive correlations between daily glossolalia activity and artificial grammar learning. These results indicate that glossolalists exhibit enhanced abilities to extract the statistical regularities of verbal information, which may be related to their unusual language abilities.

Keywords: Glossolalia; Religion; Statistical learning; Artificial grammar; Sequence learning

1. Introduction

Glossolalia ("speaking in tongues") is a rhythmic utterance of word-like strings of sounds without an everyday meaning understandable to the layperson. This verbal activity

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is regularly practiced in religious and spiritual settings to convey messages from supernatural powers (Koic, Filakovic, Nad, & Celic, 2005; Malony & Lovekin, 1985; Samarin, 1972). Speakers often report the feeling of possession by divine beings and forces, deep inspiration, and experiences of heavenly proclamations. Nowadays, glossolalia is an integral part of Pentecostal-Charismatic rituals as an accepted form of religious activity in contrast to language abnormalities outside usual social contexts (Chouiter & Annoni, 2018). Therefore, glossolalia is a culturally embedded reaction to intense religious experiences and emotions appearing in mass gatherings or a part of private religious rituals (e.g., prayer, meditation, and contemplation) with a less marked affective loading (Grady & Loewenthal, 1997).

Three main hypotheses attempt to explain the origin and mechanism of glossolalia. One view is that it as a byproduct of psychopathology (Brende & Rinsley, 1979; Francis & Robbins, 2003; Hempel, Meloy, Stern, Ozone, & Gray, 2002; Reeves, Kose, & Abubakr, 2014). According to this view, glossolalia arises out of disorganized thinking and speech in psychotic disorders, neurological conditions, or extreme reactions to severe stress and trauma. Some controversial evidence for this view comes from the investigation of patients with schizophrenia and severe "neuroses" (Cutten, 1927), borderline personality disorder (Brende & Rinsley, 1979), mania with sexual and religious delusions (Hempel et al., 2002), and temporal lobe epilepsy (Reeves et al., 2014).

Another view is that glossolalia arises out of an interaction between trance states and language processing (Goodman, 1972; Kavan, 2004). This view was championed by Goodman (1972), who analyzed phonological and suprasegmental features of glossolalic speech and found that the specific verbal behavior is the consequence of dissociation and altered state of consciousness. Dissociation and anomalous speech can be related to unusually heightened feelings and existential-aesthetic experiences (beauty, awe, power, intimacy, and faith building) (Cartledge, 2002), and glossolalia might merely be a byproduct of intense emotions (De Peza, 1996; Goodman, 1972).

Finally, many contemporary researchers argue that social learning—particularly the learning of specific linguistic skills—plays a critical role in glossolalia (Holm, 1991; Johnson, 2010; Spanos, Cross, Lepage, & Coristine, 1986; Williamson & Hood, 2011). Evidence for this view comes from a laboratory study by Spanos et al. (1986) in which training with videotaped samples and live modeling resulted in a fluent glossolalic speech in 70% of participants, suggesting a considerable role of learning. Critically, glossolalia is not an entirely random and disorganized production of language-like sounds (Kildahl, 1972; Samarin, 1972). Instead, it is characterized by specific accent, intonation, and word- and sentence-like units consisting of non-random strings of syllables, consonants, and vowels. The fundamental linguistic features of glossolalia include small phoneme numbers, accelerated speech output and melody, phonetic pulses beginning with consonants, and bars and sentences with similar lengths (Chouiter & Annoni, 2018).

Although evidence from Spanos et al. (1986), together with the linguistic features of glossolalia, suggests a role for language learning capabilities, the particular language learning mechanisms involved have not been tested. Several possible language skills may be enhanced in glossolalia. One mechanism is statistical learning. Samarin (1973)

suggested that the primary mechanism of glossolalia is linguistic "regression," which is not pathological and is not a result of dissociative trance states. In Samarin's (1973) term, "regression" means an implicitly produced stream of speech organized by phonetic rules acquired during early stages of language development, possibly via statistical learning. Conscious processes can modify these implicit phonetic processes in social settings (e.g., religious rituals). However, the relationship between implicit linguistic skills and glossolalia has not been tested empirically.

To gain insight into this relationship, we used two statistical learning tasks: artificial grammar and sequence learning. These tasks are suitable for the assessment of the gradual acquisition of phonemic regularities, which is a core feature of glossolalists who can learn primary phoneme clusters lacking the syntactic and semantic properties of intelligent speech. The approach derives from the study of infant language acquisition and skill learning, which resonates with Samarin's early developmental theory of glossolalia (Samarin, 1973). The key focus is how linguistic elements (e.g., speech sound, syllables, lexical categories, and syntactic rules) are attained and represented during implicit skill learning (Lukacs & Kemeny, 2015; Lum, Conti-Ramsden, Morgan, & Ullman, 2014). The regularly repeating statistical properties of linguistic units are computed and extracted from environmental stimuli, including frequency occurrence, segmentation, word boundaries, word form–meaning mappings, and conditional probabilities (Dienes, 2008; Fitch & Friederici, 2012; Rebuschat & Williams, 2012; Saffran, 2003; Thiessen, 2017).

In the artificial grammar learning task, participants memorize made-up pseudowords and sentences without meaning, which are generated by specific grammatical rules unknown to the listeners. The acquisition of a pseudolanguage may share similar features with the learning of glossolalic speech consisting of phoneme sequences without meaning. After the learning phase, participants are informed that the previously heard pseudowords and sentences were generated by specific rules, which are implicit and not consciously represented. The task is simply to decide whether new sentences consisting of pseudowords followed these implicit rules (grammatical items) or not (ungrammatical items) (Fitch & Friederici, 2012; Pothos, 2007; Reber, 1967) (Fig. 1). The principal mechanism of artificial grammar learning is that participants extract the statistical regularities of the pseudowords and pseudosentences during the training phase and use them to decide in the case of new stimuli.

Similar to the artificial grammar paradigm, rules can be drawn out consciously or unconsciously from repeating regularities in sequences of speech sounds, visual symbols, or serial movements during various sequence learning tasks (Clegg, Digirolamo, & Keele, 1998; Janacsek & Nemeth, 2013; Norman, 2015). These tasks are well suited for the separate investigation of the learning of linguistic regularities (e.g., non-random sequences of sounds) and nonverbal sequences (e.g., repetitive patterns of visual forms or hand movements). Artificial grammar and verbal sequence learning may tap similar underlying cognitive constructs, especially the acquisition of phonemic sequences and structures (Conway & Pisoni, 2008; Cope et al., 2017), which may be a central feature of glossolalia (Samarin, 1973).

A Artificial grammar learning

Lexical category	Pseudowords
A	biff, hep
B	cav, lum
C	vot, pell
D	dupp, loke
E	tiz, mib

Grammatical sentences	Ungrammatical sentences
Hep lum dupp.	Hep lum pel cav mib.
Biff lum tiz loke.	Biff cav lot vum.
Biff vot cav loke.	Biff pel tiz loke.
Biff cav dupp.	Loke vot biff cav.
Hep pell lum loke.	Hep loke lum pell.

B Sequence learning

Response sequence

Target letter „A" is always in position 1-3-4 on the visual display

Auditorily presented letters are random

ADCB	A
DBAC	C
BDCA	D
ACBD	B
CBAD	A
CDBA	C

Phoneme sequence

Target letter „A" is always preceded by „DC" in the auditory modality

Visually presented letters are random

CDBA	D
BCDA	C
CADB	A
BCAD	D
ACBD	C
BCDA	A

Fig. 1. Illustration of artificial grammar (A) and sequence learning (B) tasks. In the artificial grammar (A), participants listened to sentences consisting of pseudowords. After the learning phase, they were told that specific rules generated the sentences. The task was to decide whether new sentences followed the rules (grammatical items) or not (ungrammatical items). In the sequence learning task (B), participants pressed keys associated with auditorily presented letters. In the response sequence condition, the sequence of visual-spatial locations of a target letter had a repeating pattern. In the phoneme sequence condition, the sequence of the auditorily presented letters, but not their visual-spatial locations, had a repeating pattern.

Consider the sequence learning task presented in Fig. 1b. In this task, participants simply press the appropriate key when they hear a letter sound. For example, when they hear the sound "A," they respond by pressing one of four keys associated with the letter "A." In the response sequence condition, the position of keys associated with specific letters is not random. For instance, in a hypothetical sequence consisting of three successive responses, the letter "A" is always linked to the first, third, and fourth keys, respectively. The order of letter sounds is random (Fig. 1b, upper panel). Therefore, in this condition, there is a specific motor sequence to learn (key positions), whereas the sequence of verbal information (letter sounds) is not relevant. In contrast, in the phoneme sequence condition, the key positions are random, whereas the letter sounds follow a predefined sequence (Fig. 1b, lower panel). In this case, participants learn a specific string of auditorily presented verbal information. Critically, verbal and nonverbal sequence learning can be dissociated within the same task: Patients with lesions to brain areas linked to language processing show selectively impaired verbal sequence learning with intact nonverbal sequence acquisition (Goschke, Friederici, Kotz, & van Kampen, 2001). Data from patients with vascular and progressive non-fluent aphasia also indicate that the learning of

phonological sequences/artificial grammar and non-linguistic sequences is independent (Cope et al., 2017).

Based on the assumption of Samarin (1973), which highlighted the importance of implicitly acquired phonetic rules in glossolalia, the main hypothesis of the present study was that glossolalia is associated with an enhancement in statistical learning abilities for language regularities, including both artificial grammar and phonemic sequencing learning. In contrast, we hypothesized similar performances in glossolalists and non-glossolalists on the nonverbal response sequence condition, which is not directly related to language acquisition (Cope et al., 2017; Goschke et al., 2001). Finally, we tested the hypothesis that more intensive glossolalia activities would be associated with better verbal statistical learning.

2. Methods

2.1. Participants

We enrolled 30 individuals practicing glossolalia and 30 control volunteers who did not practice glossolalia from local Pentecostal and charismatic communities. The criteria of glossolalia were established according to Chouiter and Annoni (2018) and Goodman (1972): (a) few or no recognizable and meaningful words except for Biblical phrases; (b) phonemic properties similar to the language of the speaker; (c) small phoneme numbers, accelerated speech, and altered accent and melody; (d) on the phonetic level pulses begin with a consonant and bars are of equal length; (e) the primary accent falls on the first pulse of bars; (f) sentences with similar lengths; (g) an ability to speak "tongues" or ordinary language depending on the context in contrast to jargon aphasia; (h) absence of neurological illness. The first author (S.K.) and an independent rater with linguistic and pastoral psychological expertise confirmed that glossolalists meet the above-described criteria. Each glossolalist practiced in religious settings, but all of them also reported regular glossolalia activity when they were alone as a part of prayer, meditation, and contemplation. Subjective reports from the participants and observations did not indicate dissociative trance states during glossolalia, which was equivocally confirmed by the first author (S.K.) and an independent rater. The control volunteers also attended religious gatherings and listened to the glossolalic speech.

All participants received the structured clinical interview for DSM-5 (Diagnosis and Statistical Manual of Mental Disorders—5) disorders (First, Williams, Karg, & Spitzer, 2016) to exclude psychiatric disorders, including dissociative disorders. The Hungarian versions of the following tools were used to characterize the participants (Perczel-Forintos, Ajtay, Barna, Kiss, & Komlósi, 2018; Rózsa, Kő, Mészáros, Kuncz, & Mlinkó, 2010): Wechsler Adult Intelligence Scale-IV (WAIS-IV) (Wechsler, 2008), Hollingshead Four-Factor Index of Socioeconomic Status (SES) (Hollingshead, 1975), Beck Depression Inventory-II (BDI-II) (Beck, Steer, Ball, & Ranieri, 1996), Beck Anxiety Inventory (BAI) (Beck, Epstein, Brown, & Steer, 1988), and the modified Duke University Religiosity

Table 1
Characteristics of the participants

	Glossolalists (n = 30)	Non-Glossolalists (n = 30)	Effect Size (d)
Gender (male/female)	19/11	19/11	—
Age (years)	31.0 (5.6) [29, 33]	32.2 (7.0) [29.7, 34.7]	.19
Education (years)	11.2 (3.8) [9.8, 12.6]	11.3 (3.9) [9.9, 12.7]	.03
Wechsler Adult Intelligence Scale—IV (WAIS-IV)			
Full scale	102.0 (10.7) [98.2, 106]	102.4 (10.9) [98.5, 106]	.04
Working memory index	103.3 (11.4) [99.2, 107]	102.7 (10.8) [98.8, 107]	.05
Verbal comprehension index	101.9 (10.3) [98.2, 106]	104.7 (11.6) [101, 109]	.25
Hollingshead Four Factor Index (socioeconomic status)	34.5 (8.0) [31.6, 37.4]	33.6 (8.2) [30.7, 36.5]	.11
Duke University Religiosity Index (DUREL)			
Organized religious activity (1–5 points)	3.3 (1.7) [2.7, 3.9]	3.7 (2.0) [3.0, 4.4]	.22
Non-organized (private) religious activity (1–5 points)	3.5 (1.4) [3, 4]	3.6 (1.7) [3, 4.2]	.06
Intrinsic religiosity (1–5 points)	3.9 (1.6) [3.3, 4.5]	3.5 (1.5) [3, 4]	.26
Beck Depression Inventory (BDI-II)	5.7 (2.5) [4.8, 6.6]	5.9 (2.7) [4.9, 6.9]	.08
Beck Anxiety Inventory (BAI)	2.1 (0.6) [1.9, 2.3]	2.4 (0.9) [2.0, 2.7]	0.4

Note. Data are mean (standard deviation)/[95% confidence interval] except for gender distribution. The two groups did not differ in the demographic parameters ($ps > .5$).

Index (DUREL) (organized religious activity, individual religious activity, and intrinsic religiosity) (Koenig & Büssing, 2010) (Table 1).

All participants gave written informed consent. The study was approved by the National Medical Research Council (Budapest, Hungary) (ETT-TUKEB 18814). Based on the permission of the National Medical Research Council, the study was also approved by the local ethics board of the National Institute of Psychiatry and Addiction (Budapest, Hungary).

2.2. Artificial grammar learning

We used "Language P" to test artificial grammar learning (Saffran, 2002; Schuchard & Thompson, 2017). The experiment was performed under the MATLAB platform (Math-Works). The same female speaker read the sentences, which consisted of pseudowords (1.5 words/s, 70 dB). The monosyllabic pseudowords were generated according to a hierarchical phrase structure and then were assigned to one of five lexical categories. Each sentence consisted of three to five pseudowords. For the training session, we generated 50 grammatical sentences. For the testing session, 14 grammatical and 14 ungrammatical sentences were used (Fig. 1a). The hierarchical phase structure of the artificial language and the material generated according to these rules have been described previously (Saffran, 2002; Schuchard & Thompson, 2017).

The experiment was performed on two consecutive days. On the first day, participants listened to 50 grammatical sentences repeated eight times. The duration of the training session was 30–40 min. While listening to the sentences, participants watched a muted nature video to maintain their alertness. Immediately after the training session, they performed the testing phase, during which 28 sentences were presented. On the second day, the same test was completed to investigate 24-h retention.

Before the testing phase, a practice session was administered with standard instructions and examples. Participants were informed that they would hear "good" sentences that sound similar to the training sentences in contrast to "bad" sentences with an unfamiliar order of words.

The task was to decide whether a test sentence was "good" or "bad" by pressing distinct keys (1—good, 2—wrong). Before the auditory presentation of the test sentence, a fixation cross and a ready signal were displayed for 500 ms. The duration of the intertrial interval (blank screen) 2,000 ms.

There were two dependent measures to characterize the effectiveness of artificial grammar learning. First, the percentage of correct decisions regarding the new sentences was calculated. Second, we determined the sensitivity index (d') to control response bias (a bias toward responding "good" or "bad" during the testing phase). We calculated the sensitivity index: $d' = z$-score (hits: correct identification of grammatical sentences)—z-score (false alarms: incorrect identification of ungrammatical sentences as being grammatical) (Schuchard & Thompson, 2017).

2.3. Sequence learning

The procedure of sequence learning followed a previously published protocol (Goschke et al., 2001). The task was to match visually and verbally presented letters by pressing the appropriate keys. Stimuli were four letters (A, B, C, and D) spoken in the same female voice as in the artificial grammar experiment. In the visual modality, stimuli were presented as uppercase letters in a horizontal row on the computer screen (Arial, 18-pt font). The location of the letters in the row changed from trial to trial. Each letter was associated with a key on a response pad (Cedrus RB-740). The experimental trials began with the visual presentation of the four letters in a row. After a delay phase (500 ms), we exposed one of the four letters in the auditory modality. Participants pressed the response key associated with the location of the letter presented in the auditory modality. For example, when the visual presentation of the letters "DCBA" was followed by the auditory presentation of the letter "A," the participant had to press the rightmost key. The intertrial-interval was 500 ms.

There were two conditions (Fig. 1b). In the response sequence condition, the sequence of the visual-spatial locations of a target letter showed a repeating and regular pattern. In contrast, in the phoneme sequence condition, the sequence of the auditorily presented letters, but not their visual-spatial locations, showed a regularly repeating pattern. For example, participants could acquire that the auditorily presented letters "ABB" were followed by the letter "D," but they could not predict the next response because there was no

regular letter sequence in the visual display (Fig. 1b). The structure of both sequence and phoneme conditions was the following: 80 practice trials, three sequence blocks of 20 repetitions of an 8-trial sequence (altogether 160 trials in each sequence block), 80 trials with a pseudorandom sequence, and 80 trials with 10 repetitions of the structured sequence. Each participant completed one response sequence condition and one phoneme sequence condition. The order of these conditions was counterbalanced. The dependent measures were mean response times and error rate. We also calculated response time cost (ms) in the random block (response time in the random block minus response time in the sequence block preceding the random block).

Following the sequence learning task, participants completed an explicit reproduction test in which they produced a 30-trial sequence. Regarding the response sequence condition, they learned that a regular pattern in the keypresses had occurred in the training phase, and they were requested to reproduce that by using the same keys consciously. Regarding the phoneme sequence condition, participants were told that a regular pattern had occurred in the auditorily presented letters, and they verbally retrieved this sequence. We calculated the reproduction index for each participant as described by Goschke et al. (2001). To this end, non-overlapping 2-8-element chunks from the previous training phase were counted. The reproduction index referred to the percentage of elements that were included in the correct chunks (>3 elements). For example, in the case of 2 correct 4-element chunks, and 3 correct 5-element chunks, the reproduction index was $100 \times (2 \times 4 + 3 \times 5)/30 = 76.7$. Baseline performance was obtained from 30 healthy control subjects (not included in the present study), who produced the 30-element key presses without a training phase (i.e., the responses were random). The baseline reproduction index for the response sequence task was 25.4 ($SD = 5.9$), whereas, for the phoneme sequence learning task, we obtained a reproduction index of 27.9 ($SD = 7.2$).

2.4. Statistical analysis

We applied STATISTICA 13.0 (Tibco, Palo Alto) and JASP (version 0.9.2., JASP Team) for data analysis. First, data distribution (Lillefors test) and homogeneity of variance (Levene's test) were checked to justify further parametric tests. Repeated measures analyses of variance (ANOVAS) were performed on the dependent variables form the artificial grammar learning test (d' and % correct) and response/phoneme sequence learning tasks (response time and error rates). Tukey's Honestly Significant Difference (HSD) tests were used for post hoc comparisons. Each post hoc comparison was repeated using a Bayesian approach. F tests were used to explore between-group differences for a linear trend in sequence learning. Effect size values (partial η^2) were calculated for each comparison. We also calculated Spearman's product-moment correlation coefficients (rs) between the measures of glossolalia and test performances. Type I errors were corrected with the Bonferroni method where appropriate. The level of statistical significance was set at $\alpha < .05$.

3. Results

3.1. Artificial grammar learning

We performed a group (glossolalists vs. controls) by assessment (immediate vs. delayed) ANOVA on d'. This analysis indicated significant main effects of group (F (1,58) = 17.31, $p < .001$, $\eta^2 = 0.23$), assessment ($F(1,58) = 87.66$, $p < .001$, $\eta^2 = .60$), and an interaction between group and assessment ($F(1,58) = 45.59$, $p < .001$, $\eta^2 = .44$). Tukey's HSD tests and Bayesian t tests revealed higher d' values in the glossolalia group relative to the control volunteers at both immediate and delayed assessments (p [immediate] = .03; p [delayed] < .001; BF_{10} [immediate] = 6.88; BF_{10} [delayed] = 10687). Furthermore, in the control group, the 24-h delay led to a significant reduction of d' ($p < .001$), whereas, in the glossolalia group, the d' values measured immediately after the training phase and after 24 h did not differ ($p = .27$) (Fig. 2A).

Regarding performance (% correct) in the artificial grammar learning test, we also found significant main effects of group ($F(1,58) = 35.10$, $p < .001$, $\eta^2 = .38$) and assessment ($F(1,58) = 53.90$, $p < .001$, $\eta^2 = .48$), but the two-way interaction between group and assessment was not significant ($p = .14$). The post hoc analysis indicated that individuals with glossolalia outperformed the control group at both assessments (ps < .001; BF_{10} [immediate] = 26666; BF_{10} [delayed] = 114692) (Fig. 2B).

3.2. Sequence learning

3.2.1. Response and phoneme sequence learning

The results are shown in Fig. 3. First, we performed an ANOVA on response time values with group (glossolalia vs. controls) as the between-subjects factor, a sequence type (response vs. phoneme) and blocks (5) as the within-subjects factors. The ANOVA yielded a significant main effect of blocks ($F(4,232) = 395.0$, $p < .001$, $\eta^2 = .87$) and a two-way interaction between group and blocks ($F(4,232) = 26.69$, $p < .001$, $\eta^2 = .32$). Critically, the three-way interaction among group, sequence type, and blocks was also significant (F (4,232) = 23.0, $p < .001$, $\eta^2 = .28$). The remaining main effects and interactions were not significant (ps > 0.1).

Next, we used planned comparisons (F tests) to investigate potential differences in the linear characteristics of the learning curve during the first three blocks. In the phoneme sequence learning task, this analysis indicated a significant difference for linear trend (glossolalia vs. controls), revealing a more pronounced reduction of response time in the glossolalia group relative to the control participants during the first three blocks (F (1,58) = 64.11, $p < .001$) (Fig. 3). Indeed, in the third block, glossolalists were significantly faster than controls (Tukey's HSD, $p = .01$; Bayesian t test: $BF_{10} = 15.78$). In the response sequence learning condition, there was no significant difference between glossolalists and controls (ANOVA main effect of the group: $p = .64$) (Fig. 3).

The mean error rates across the three first training blocks were low (<5%) in both groups. There were no significant differences between glossolalists and controls ($p > .5$).
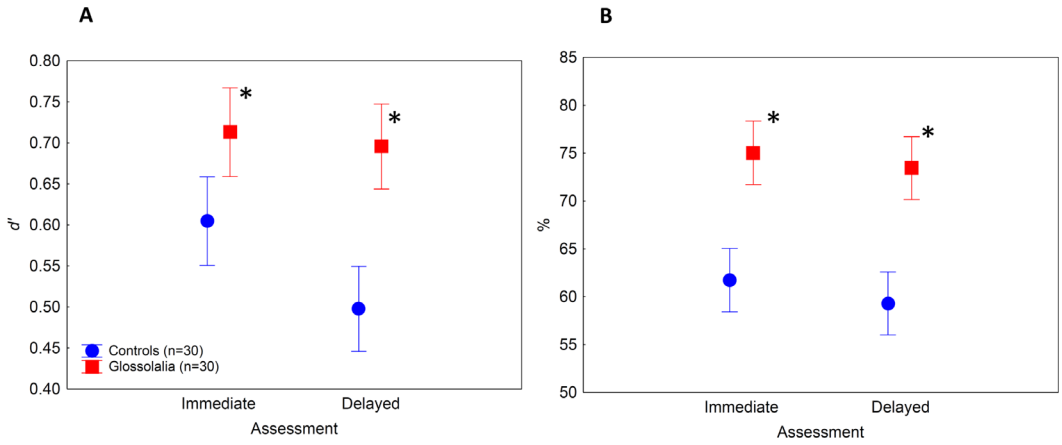
Fig. 2. Results from the artificial grammar learning task. Mean sensitivity values *(d′)* and percentage correct scores (%) are shown in the case of immediate and delayed assessment. Error bars indicate 95% confidence intervals. The glossolalists outperformed the control group on each condition. *$p < .05$.
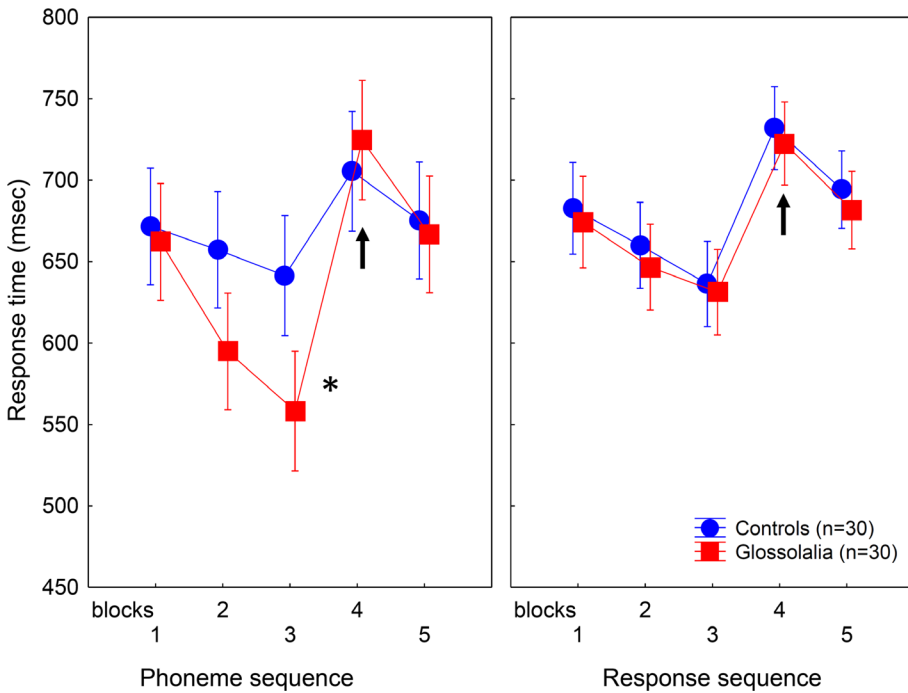
Fig. 3. Mean response time from the sequence learning task. Error bars indicate 95% confidence intervals. During the first three blocks, glossolalists showed a steeper reduction of response time (more efficient learning) relative to non-glossolalists in the phoneme sequence condition. In the third block, glossolalists were faster than controls (*$p = .01$). There was a prolonged response time in the fourth block (indicated by an arrow) when random sequences were presented instead of the sequences acquired during the preceding three blocks.
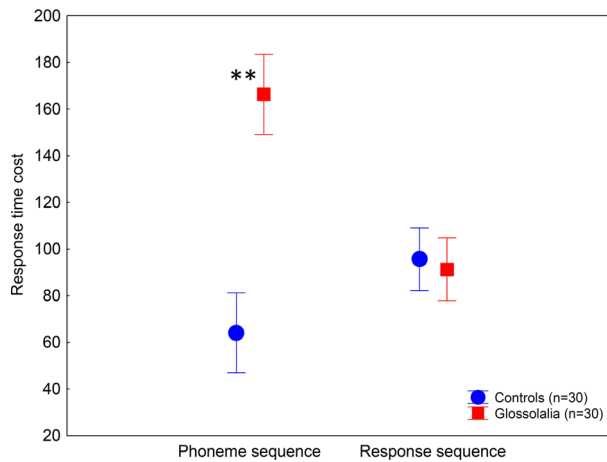
Fig. 4. Mean response time cost (response time in the fourth block minus response time in the third block). Error bars indicate 95% confidence intervals. The glossolalists showed greater response time cost in the phoneme sequence condition relative to the control group, which indicates more efficient sequence learning. **$p < .001$.

3.2.2. Response time cost

We calculated response time cost: response time in the fourth block minus response time in the third block. If the sequence learning is successful, response time is gradually decreasing during the first three blocks. However, there is a prolonged response time in the fourth block when random sequences are presented instead of the sequences acquired during the preceding three blocks. Therefore, higher response time costs reflect more efficient learning.

The ANOVA conducted on the response time cost values indicated a significant main effect of group ($F(1,58) = 44.92$, $p < .001$, $\eta^2 = .44$) and the type of response time cost (response vs. phoneme sequence) ($F(1,58) = 7.21$, $p = .01$, $\eta^2 = .11$). The two-way interaction was significant ($F(1,58) = 43.51$, $p < .001$, $\eta^2 = .43$). Tukey's HSD tests and Bayesian t tests revealed that individuals with glossolalia showed higher response time costs in the phoneme sequence learning task relative to the controls ($p < .001$; $BF_{10} = 5.26e+8$), whereas in the response sequence learning task, the two groups exhibited nearly identical values ($p > .5$) (Fig. 4).

3.2.3. Sequence reproduction index

We found no significant differences between glossolalists and controls in the conscious reproduction of response and phoneme sequences (glossolalia: M [response] = 26.3, $SD = 8.4$; M [phoneme]: 23.9, $SD = 9.4$; controls: M [response] = 27.6, $SD = 9.0$; M [phoneme]: 24.2, $SD = 8.2$; ps > .2). In addition, glossolalists did not differ from the baseline values, which were obtained from individuals with no previous training (non-
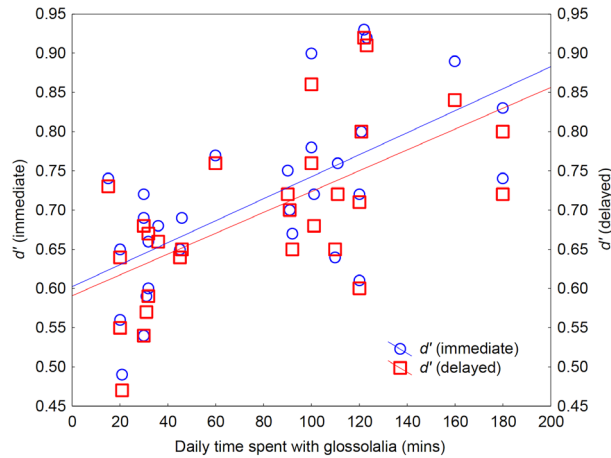
Fig. 5. Correlations between artificial grammar learning performances (sensitivity index *[d′]* from immediate and delayed conditions) and the time spent with glossolalia activity. Both correlations were significant (*d′* [immediate]: *r* = .64; *d′* [delayed]: *r* = .63, *p*s < .001).

trained subjects not included in the present study, n = 30: *M* [response] = 25.4, *SD* = 5.9; *M* [phoneme] = 27.9, *SD* = 7.2; *p*s > .2).

3.3. Correlations between glossolalia, artificial grammar learning, and sequence learning

We calculated conventional and Bayesian correlation coefficients (controlled for age, education, gender, IQ, socioeconomic status, and DUREL scores) between the average daily time spent with glossolalia, *d′*, and response time in the first three blocks (both response and phoneme sequence conditions). There were significant positive correlations between the average daily glossolalia activity and *d′* from the artificial grammar learning task (immediate: *r* = .64, *p* < .001; BF_{10} = 203.6; delayed: *r* = .63, *p* < .001; BF_{10} = 158.7) (Fig. 5). We found no significant correlations between glossolalia activity and response time in the response and phoneme sequence learning tasks (Table 2).

We also calculated the correlations between the WAIS-IV working memory index, *d′* from the artificial grammar learning task, response time (block 3), and response time cost from the sequence learning tasks. There were no significant correlations between the abovementioned measures of working memory and statistical learning (Table 2).

4. Discussion

The present study demonstrated enhanced verbal learning abilities in glossolalists in artificial grammar and verbal sequence learning. Relative to control individuals, glossolalists showed boosted abilities to extract statistical regularities from verbal information. They effectively acquired the rules of artificial grammar and used that in decision-making

Table 2
Correlation between learning performances and demographic parameters in individuals with glossolalia

	Time Spent with Glossolalia (min/day)	Age	Education	WAIS-IV Full Scale	WAIS-IV Working Memory	WAIS-IV Verbal	DUREL Organized Religion	DUREL Private Religion	DUREL Intrinsic Religiosity	BDI	BAI
Artificial grammar (d – immediate)	0.64*	−0.01	0.06	−0.05	−0.02	0.05	0.02	0.08	−0.07	0.00	0.04
Artificial grammar (d – delayed)	0.63*	0.06	−0.03	0.10	−0.07	0.09	0.01	−0.08	−0.08	−0.09	0.02
Phoneme sequence (block 3 reaction time)	−0.19	−0.09	0.02	0.02	−0.04	0.09	0.06	−0.00	−0.05	−0.02	0.08
Phoneme sequence (response time cost)	0.25	0.01	−0.04	−0.06	−0.03	0.05	−0.05	−0.10	−0.04	−0.04	−0.06
Response sequence (block 3 reaction time)	0.10	0.02	0.04	0.05	−0.05	0.11	−0.10	−0.04	0.06	0.06	−0.09
Response sequence (response time cost)	−0.01	0.03	−0.02	−0.03	−0.06	−0.03	0.06	0.01	0.08	−0.00	−0.07

Note. The table shows Pearson's product moment correlation coefficients.
BAI, Beck Anxiety Inventory; BDI, Beck Depression Inventory-II; DUREL, Duke University Religiosity Index; WAIS-IV, Wechsler Adult Intelligence Scale-IV.
*$p < .001$ (significant correlations following Bonferroni correction, $p = .05/66 = .0008$).

in the case of novel stimuli to discriminate between grammatical and non-grammatical items. Moreover, glossolalists exhibited a higher 24-h retention capacity of grammatical rules relative to the control volunteers.

In the sequence learning task, glossolalists outperformed the control group in verbal, but not visual-response sequences. This latter ability was implicit because, similar to the control volunteers, glossolalists were not able to intentionally and consciously reproduce the acquired sequences. Altogether, we found that glossolalists showed enhanced abilities to detect and to acquire statistical regularities in linguistic surface structures, which does not require intentionality, conscious awareness, or semantic processes. It is important to note that glossolalists and controls achieved similar scores on measures of controlled information processing and language understanding (WAIS-IV working memory and verbal comprehension index, respectively).

The non-glossolalist individuals, who served as controls in this study, were from the same Pentecostal community, and they all listened to the glossolalic speech. There is no clear answer to why they could not produce glossolalia. Based on our data, it is tempting to speculate that they did not have sufficient verbal learning skills, but other explanations are also possible. Their religious attributions were notable. They did not struggle with their inability to produce glossolalic speech but believed that the Holy Spirit gave them other presents and charismas (e.g., prophecy and healing).

The results of the present study resonate with the learning theory of glossolalia (Holm, 1991; Johnson, 2010; Spanos et al., 1986; Williamson & Hood, 2011). We demonstrated enhanced verbal learning in laboratory circumstances on statistical learning tasks, which indicates that some aspects of glossolalia cannot be explained by heightened arousal, intense emotions, and social-situational influences during religious community rituals. Moreover, in the artificial grammar learning task, the efficacy of learning displayed a positive relationship with the time spent with glossolalia. This relationship may indicate that glossolalia practice under real-world circumstances results in enhanced statistical verbal learning. However, the cross-sectional and correlational nature of the present study is a definitive limitation on the interpretation of causal relationships. It is also possible that individuals who are primarily involved in glossolalia rituals are characterized by superior baseline statistical learning, which eventually makes them more efficient in the acquisition of glossolalia skills. Of course, it is not likely that good statistical learning is a sole causal factor in glossolalia, but it might contribute to the degree to which vocalizations exhibit a patterned structure.

Our results do not support the claim that glossolalia is necessarily linked to psychopathology (Brende & Rinsley, 1979; Francis & Robbins, 2003; Hempel et al., 2002; Reeves et al., 2014) because none of the volunteers in the present study had a clinical diagnosis as revealed by autobiography and structured clinical interviews. Notably, individuals with some psychiatric disorders (e.g., schizophrenia and mood disorders) fail to show effective statistical learning on artificial grammar and sequence learning tasks (Chrobak et al., 2017; Horan et al., 2008; Janacsek, Borbely-Ipkovich, Nemeth, & Gonda, 2018). If glossolalists showed the symptoms of schizophrenia or mood disorders, we would expect impaired learning performances. But that was not the case. Finally, even

mild depressive and anxious symptoms cannot play an essential role in glossolalia, because our glossolalia and non-glossolalia samples did not differ in subclinical negative experiences. However, it does not mean that glossolalia is never associated with mental disorders because we had data only from a small group of individuals who otherwise agreed to participate in research. Our biased sample is not suitable to completely refute the psychopathological hypothesis of glossolalia, at least in some cases.

It is essential to bear in mind that glossolalia is not a unitary phenomenon. Some individuals convey divine messages in a private setting and speak calmly with an intact awareness of their verbal behavior. Others mainly practice glossolalia in religious community settings with high excitation, emotional intensity, ecstasy, and less awareness (Grady & Loewenthal, 1997). These types may be differentially linked to psychopathology. However, the classification of Grady and Loewenthal (1997) could not be used in our study because each glossolalist practiced both types of verbal behavior: They regularly spoke in communities and also lean on glossolalia in their private prayers, meditations, and contemplations. None of our participants experienced trance states.

It is interesting to speculate on the neuronal correlates of glossolalia in light of our current findings. Critically, Newberg, Wintering, Morgan, and Waldman (2006) demonstrated a significant decrease in the activity of the prefrontal cortex during glossolalia, which may indicate weakened intentionality and executive control over vocalization. This finding is relevant to understand enhanced statistical learning because there might be a competitive relationship between the prefrontal executive network and the frontostriatal network underlying implicit learning (Filoteo, Lauritzen, & Maddox, 2010; Nemeth, Janacsek, Polner, & Kovacs, 2013; Virag et al., 2015). For example, Virag et al. (2015) demonstrated a negative relationship between a composite executive score (digit span, counting span, listening span, and letter fluency) and alternating serial reaction time performance. Moreover, patients with chronic alcohol use disorder, who displayed marked executive dysfunctions, were characterized by intact learning on the implicit serial reaction time task (Virag et al., 2015). It has also been proposed that the frontostriatal system is implicated in language acquisition. For example, meta-analytic evidence indicates that children with specific language impairment (delayed or disordered development of language acquisition and production) also show impairments on the serial reaction time task (Lum et al., 2014). Therefore, it is possible that glossolalists downregulate their executive network during artificial grammar and verbal sequence tasks, which may result in enhanced statistical learning. However, we found no differences between glossolalists and non-glossolalists in working memory, and there were no correlations between working memory and statistical learning. Future studies should explore the possibility that the executive network is downregulated in glossolalia.

From a more general point of view, our study described a novel type of dissociation between verbal and nonverbal sequence learning. Previously, Goschke et al. (2001) demonstrated that patients with Broca's aphasia displayed a selective impairment in the learning of phoneme sequences, whereas their performance on the response sequence learning task was spared. The authors interpreted these findings within a neural

framework, suggesting that there may be partially different brain systems supporting the procedural learning of verbal and nonverbal sequences (Goschke et al., 2001). The present findings support this assumption, demonstrating that glossolalia can be conceptualized as a mirror image of Broca's aphasia: Glossolalists show boosted phoneme sequence learning, whereas Broca's aphasics are less efficient on this task relative to controls. According to Chouiter and Annoni (2018), aphasia and glossolalia are fundamentally different conditions. For example, the language characteristics of glossolalia involve small phoneme numbers, morphological structures, and accelerated speech. In contrast, these features in language disorders following brain lesions, with a particular reference to jargon aphasia, are highly heterogeneous, sometimes characterized by paraphasia and neologisms (Lecours & Vanier-Clément, 1976). Moreover, individuals with chronic aphasia show stable deficits, whereas glossolalists can switch from glossolalia to ordinary language (Chouiter & Annoni, 2018).

Our study is not without limitations. First, the sample size was small, including Hungarian-speaking glossolalists from a specific religious community. Therefore, the results must be replicated in a larger independent sample. Second, given the nature of convenience sampling, the results are not representative of the general population, and our data do not exclude the possibility that a particular type of glossolalia may be associated with mental disorders. Third, although we demonstrated a relationship between verbal statistical learning and glossolalia, we did not test the learning theory directly by training individuals to glossolalic speech under real-world circumstances. Fourth, much of what we know about glossolalia derives from the study of native speakers of English (Samarin, 1973). The difference between English versus Hungarian Pentecostal glossolalia has not been explored. Nevertheless, the criteria of Chouiter and Annoni (2018) could be applied to Hungarian glossolalia, which was independently confirmed by the first author (S.K.) and a rater with expertise in linguistics and psychology.

In conclusion, the present results indicate that Hungarian Pentecostal glossolalists without mental disorders display enhanced verbal statistical learning, which is associated with the time spent with glossolalia. Future studies are warranted to extend these findings by the investigation of different types of glossolalia and the role of statistical learning under real-world circumstances.

Acknowledgments

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