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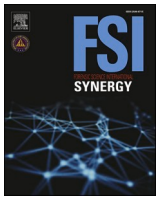

Effect of stroke-induced memory impairment on handwriting–A forensic case study

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ABSTRACT

Handwriting is an acquired neuromuscular skill that relies on motor memory and brain function, which make it vulnerable to impairments caused by physical or mental conditions. This paper presents a forensic case study comparing pre- and post-stroke Devnagari writing samples of a post-neurosurgery memory-impaired patient. The study aimed to assess the feasibility, reliability, and limitations of handwriting identification, in such cases. Results revealed that there are significant differences between pre- and post-stroke handwritings, indicating distinct master pattern and potentially different writers. In the absence of medical history, a false negative opinion could have been generated in this case. This study highlights the need for contemporaneous specimens, careful evaluation, and integration of medical history in forensic document examination. It is, certainly, a grey area, emphasizing the need for further research.

1. Introduction

Handwriting is a neuromuscular controlled motor activity in which hand (or the foot) merely acts as a humble servant of the brain while producing the desired writing through the neuromuscular reflexes. Briefly explaining intricacies of the writing process, Sulner stated that in order to guide the writing instrument to write, the brain has to send the message through the nervous system which, on the way, may encounter unusual physical and mental interruption varying from simple muscular weakness to the complicated illnesses [1]. Morris described four stages of writing development prior to that of graphic maturity [2]. The writing characteristics and qualities of letters and combinations being written physiologically, are stored as habitual or master patterns in the brain, which are recalled from its memory and finally reproduced unconsciously on paper. Primarily, there are eight key components of handwriting skill as shown in Fig. 1, of which, memory is the most essential one for independent production of handwriting [3].

Oyigeya stated that good, or poor memorizing and recalling ability invariably affects the production and overall quality of handwriting [4]. Dinnes, reported that some survivors of traumatic brain injuries ("TBI") lost their writing ability due to neurological assaults, affecting their language and cognition faculty [5]. Allen stated that there are specific areas of the brain associated with language and vocabulary which are essential components of handwriting production. Among others, handwriting responds to several skills linked with the brain functions like memory recall, mental attention, visual focusing, concentration with awareness, and eye-hand coordination that we need while performing routine activities throughout our lives. As an offshoot of memory loss, any brain-injury related lesion that disrupts the motor pattern may result in a an unskilled handwriting resembling an illegible scribble [6]. Sulner linked several mental disorders, especially due to the use of alcohol and drugs, with their respective effects on handwriting [1]. Caligiuri explained the phenomenon of interaction between the human brain and the writing instrument involved in the act of writing through the motor and association cortices [7]. Mohammed stated that learned handwriting is controlled by a motor program probably residing within a network of cortical and subcortical brain areas and their pathways [8]. Studies by Palmis [9], Planton [10] and Berryhill [11] specified several brain areas as contributing to the writing process, whereas another study [12] suggested that seven areas of the brain are involved in the process of writing execution as shown in Fig. 2, indicating thereby that the human brain is like a group of experts, each part thereof has its own special responsibilities and collectively they work as a single unit.

Many other research studies discuss how handwriting serves as a

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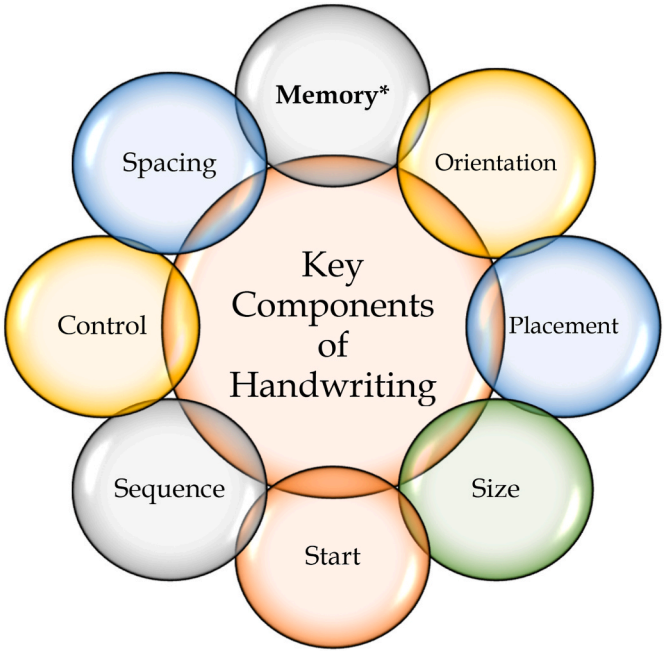

Fig. 1. Key components of handwriting skills.

marker for diagnosing or monitoring various health and neurological conditions [14–23]. Some studies examine impact of disorders like Alzheimer's [14–16], Parkinson's [17–19], schizophrenia [20], Rheumatoid arthritis (RA) [22], essential tremors [23], and Aphasia [24] on handwriting dynamics, such as pen pressure, fluency, and motor control. Hence, in nutshell, handwriting execution invariably involves the brain functions and, injury to its specific parts, has the potential to affect the handwriting production materially. This being so, memory-impairment materially affects the handwriting execution process to the extent that a patient's post-stroke writings may exhibit consistent dissimilarities with his pre-stroke writings, laying a trap for the document examiner to commit error in identification. The aforesaid studies clearly indicate that handwriting examiners should consider health and neurological conditions while analyzing handwriting. However, the literature survey indicates that case studies related to effects of memory loss on handwriting are too rare to find. Dinnes supported our belief stating that scarce literature exists about TBI's effect on writing abilities [5]. Hence, the authors felt the necessity of reporting this case for the ultimate benefit of the FDE's.

2. Materials and methods

2.1. Sample acquisition

For current study, pre- and post-stroke Devnagari writing samples belonging to a post-neurosurgery memory-impaired patient undergoing rehabilitation treatment in a local hospital were procured with consent from both the patient and his family.

The post-stroke Devnagari writing samples were procured on different occasions during the period 2003–2006 and were marked as A-1 to A-4 (Figs. 3–6). After being discharged from the hospital, the patient could not be contacted and as such his subsequent or earlier writing samples could not be obtained.

The pre-stroke handwriting samples included two inland letters marked B-1 and B-2 (Figs. 7–8) written in Devnagari, pertaining to the year 1982 and 1986. However, the writing samples of the intervening period were not readily available at that time.

2.2. Sample analysis

The basic ACE (Analysis, Comparison and Evaluation) methodology, which is applied in various scientific domains to investigate unknown materials by examining the relevant and specific features, was used for handwriting analysis in this case. In this methodology, 'analysis' begins with careful examination of the unknown and known items one by one to isolate the discriminating features therein. The next step involves 'comparison' of the distinct features identified through analysis between the known and the unknown samples using the principle of like with like comparison. The comparison process is then followed by 'evaluation' of the similarities and/or differences, as well as the unaccounted features, if any, both individually and collectively, between them on the basis of their qualitative and quantitative significance. During evaluation, weightage of each and every feature is assessed taking into account its underlying cause, independence, or probable chance of occurrence [25].

For collective assessment, interpretation, and illustration of various similarities and dissimilarities between the post-and pre-stroke writings, juxtaposed comparison charts (Figs. 9 and 10) were prepared. Based on the observations of forensic examination, appropriate conclusions of authorship were drawn in accordance with the basic principles of handwriting identification.

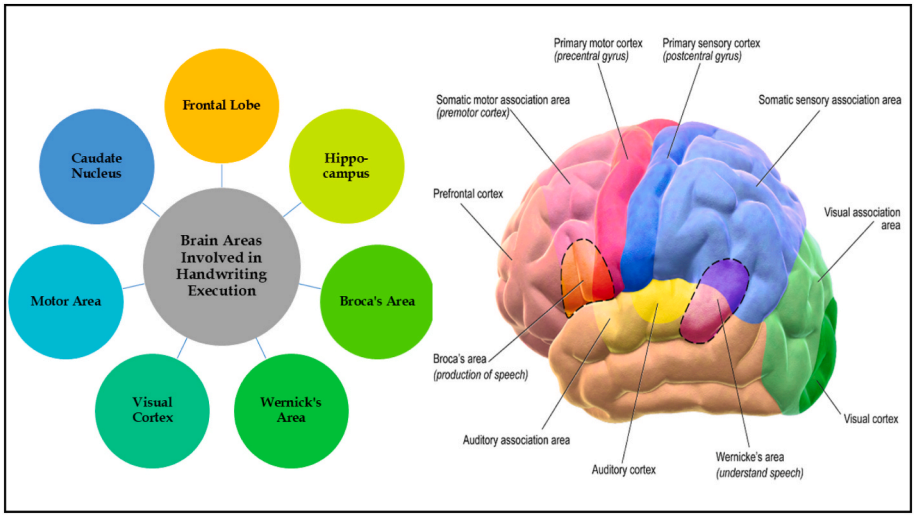

Fig. 2. Areas of Brain involved in execution of Handwriting (A portion of figure taken from Ref. [13]).

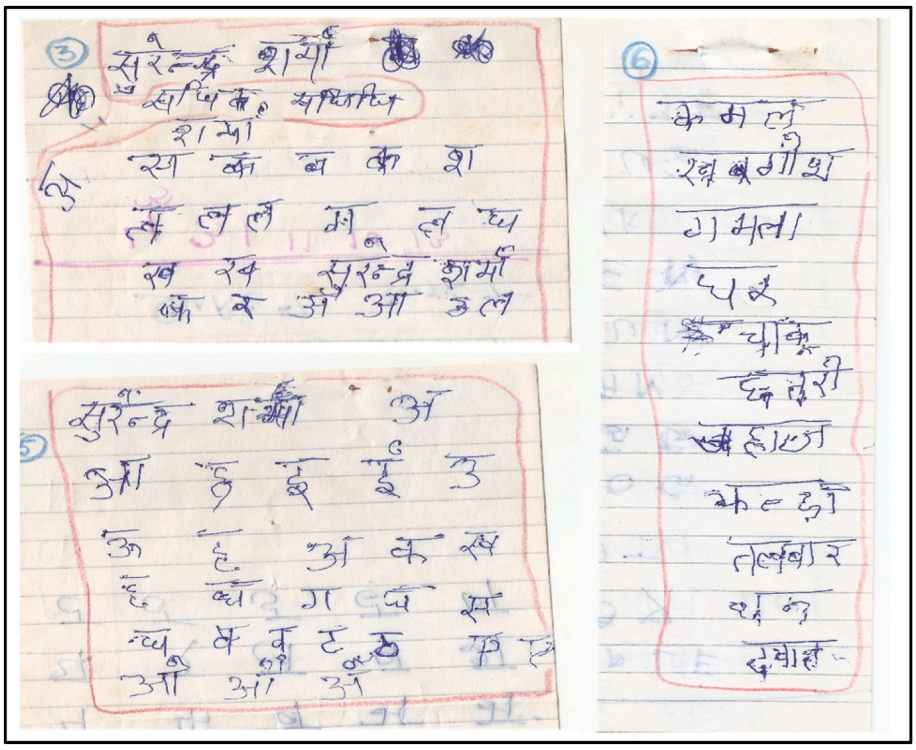

Fig. 3. Handwriting samples of patient collected post-stroke marked as A-1 belonging to year 2003.

3. Forensic examination

3.1. Details of examiners

The initial examination of the samples was conducted by one of the authors having more than 25 years' experience as a State Forensic Document Examiner (FDE), who had himself collected the post-stroke writing samples from his acquainted patient undergoing post-neurosurgery rehabilitation treatment. The pre-stroke samples were provided by the patient's relatives voluntarily, as per his request. The second examination was conducted by another government examiner having an experience of about 50 years, who also happens to be an author of the case study. As such, the authors had a prior knowledge that both the pre-and post-stroke writing samples belonged to the same stroke patient, though the actual stroke-related clinical history of the patient was not as such available with the authors. The patient could not be contacted thereafter. Incidentally, such contextual information including clinical history of the patient writer may not be readily supplied to the FDE's, most of the time.

3.2. Details of examination

The post-stroke writings marked A-1 to A-4 (hereinafter referred to as Set-1) were forensically examined and compared with the pre-stroke writings marked B-1 to B-2 (hereinafter referred to as Set-2) to find out the points of similarity and dissimilarity between them. Both the writings marked B-1 and B-2 pertaining to set-2 appear to have been executed ex-tempore, freely and speedily, by the natural neuromuscular reflexes originating directly from the brain's memory, indicating a graphically matured writer. Their inter-se examination shows consistency in movement, skill, speed, slant, alignment, relative size and proportion of various letters/strokes and their combinations indicating thereby that both these writings were probably written during the same period and by the same writer. On the other hand, the writings marked A-1 to A-4, pertaining to set-1, lack naturalness, freedom, fluency and speed indicating thereby that they were not produced by the natural neuromuscular reflexes. As a result of sustained practice, slightly improvised skill was observed in the post-stroke writing of the year 2006 (A4) compared to that of the preceding years 2003–2005 (i.e., A1-A3). Notwithstanding considerably lower order of movement and skill of the writer, all these writings (i.e., A1-A4) show consistency among themselves indicating a single author. Intercomparison of writings contained in both the sets reveals that the respective order of movement, line quality, skill and muscular coordination of set-1 is substantially lower than that of the set-2. The obvious disparities in line quality and letter formations between the two sets of writings as described above, prima facia, appear to be basic and structural indicating different authorships. To facilitate a comparative study, the general characteristics of both the sets are given in Table-1 below:

Some points of dissimilarity as well as similarity in non-general (i.e., letter-specific) features are described in Table-2 and illustrated in Figs. 9 and 10 below.

3.3. Evidence evaluation

While evaluating the significance of both the general and non-general features as described above, it is noteworthy to consider that there was a gap of around 20 years in the execution of Sets-1 and 2, and comparison standards of the intervening period were not available. Undeniably, some illnesses, trauma, and emotions may cause sudden unforeseen changes in handwriting. Several physiological, neurological and psychopathological changes may occur during this period resulting in astonishing apparition of odd handwriting characteristics in post-stroke writings of the same person. Further, there was no specific information regarding the age of the subject under study. Under the circumstances, contemporaneous standards were absolutely necessary for comparison. Going a step further, considering many internal and external factors affecting the person's handwriting, it was imperative that, during procurement of comparison standards, the matching of conditions and circumstances between the two sets of writings was ensured to examine and verify if the observed differences in shape, quality, or particular movements, could (or could not) be accounted for

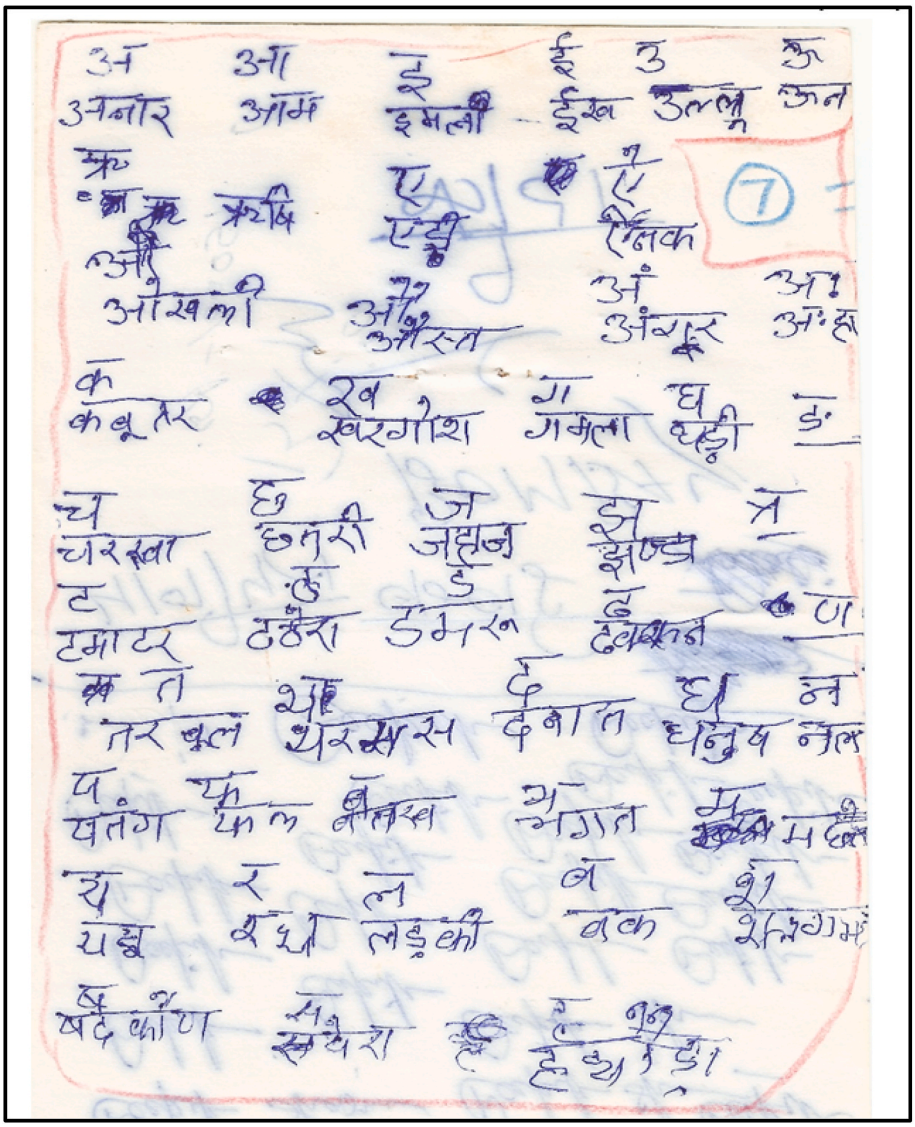

Fig. 4. Handwriting samples of patient collected post-stroke marked as A-2 belonging to year 2004.

from them. Apparently, the post-stroke writings resembled the writings of school children who were still in the elementary stage of handwriting acquisition and, therefore, being underdeveloped, they lack individuality needed for their identification. Such reversion from the graphic maturity to the childhood stage, could be the offshoot of unusual mental condition of the writer [25].

On evaluation, it was found that the similarities in writing characteristics, as described above, could be coincidental and insignificant and, hence, misleading; more so, in the wake of dominant dissimilarities between the two sets of writings. The said finding was consistent with the statement of Harrison that difficulties in identification are more likely to arise where the handwritings under examination are underdeveloped in that they have been written consciously and carefully, letter by letter, to match the copybook forms, but lacks automatic memory needed to write in an instinctive and reflex manner, with attention concentrated more on what is being written than on how it is being written [26].

Prima facia, the post stroke writings showed consistent dissimilarities, as described earlier, vis-à-vis the pre-stroke writings, indicating two different writers. However, their nature and significance needed to be thoroughly evaluated before treating them as basic, structural, or fundamental disparities; because, as stated by Harralson, some apparent differences may not be the true differences indicative of different authorship, but simply intra-writer variations resulting from some unforeseen circumstances arising out of personal or health issues [25]. Hence, such dissimilarities could not be treated as reliable indicators of different authorship, whereas, the similarities therein were neither significant nor sufficient for an opinion of common authorship.

4. Results

Based on the forensic examination as well as the neurological considerations, the following results were obtained.

4.1. Lack of individuality in post-stroke writings

The post-stroke writings marked A1 to A4 (Set-1) lack sufficient individuality needed for their identification.

4.2. Likelihood of different authorship

Prima facia, the possibility of different authorship of the pre and post stroke writings, appears to be much more likely than that of their common authorship.

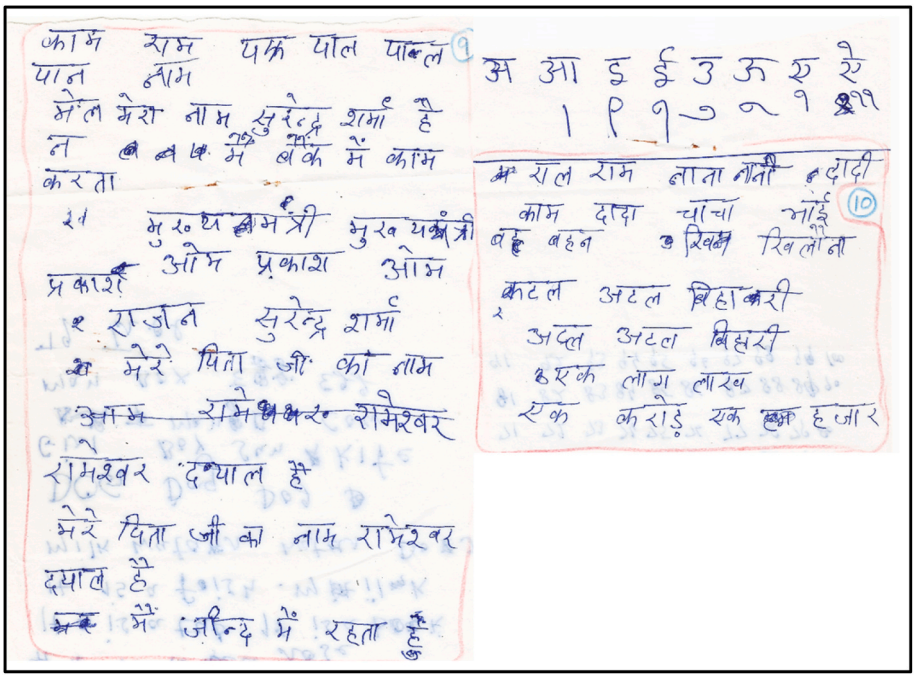

Fig. 5. Handwriting samples of patient collected post-stroke marked as A-3 belonging to year 2005.

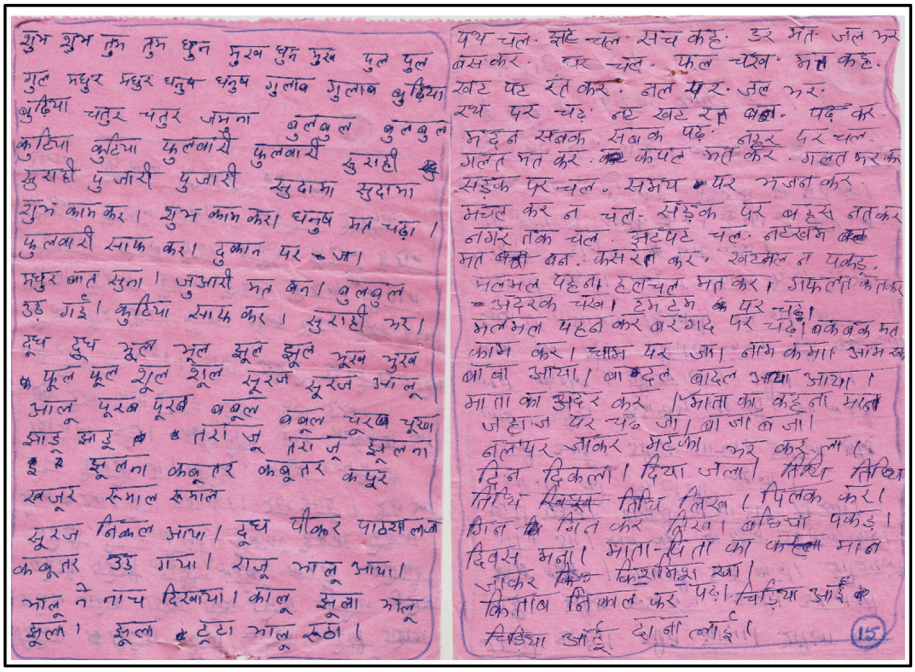

Fig. 6. Handwriting samples of patient collected post-stroke marked as A-4 belonging to year 2006.

4.3. Possibility of common authorship

The possibility of common authorship of the pre-and post-stroke writings, howsoever remote, cannot be ruled out.

4.4. Inconclusive opinion on authorship

No definite opinion could be expressed regarding the common authorship of the pre- and post-stroke writings, or otherwise, on the basis of material supplied.

4.5. Need for contemporaneous standards and medical history

Contemporaneous pre-stroke standards contiguous to the post-stroke writings, as far as possible, and clinical & medical history of the subject needed to be examined before attempting either to link or to rule out the possibility of the subject being the author of the post-stroke writings.

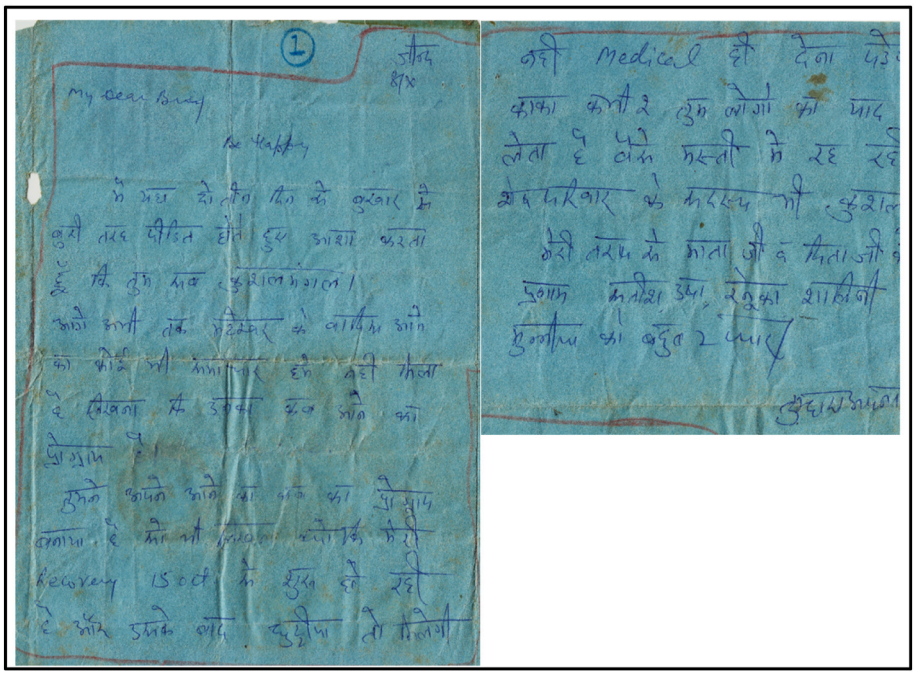

Fig. 7. Handwriting samples of patient collected pre-stroke marked as B-1 belonging to year 1982.

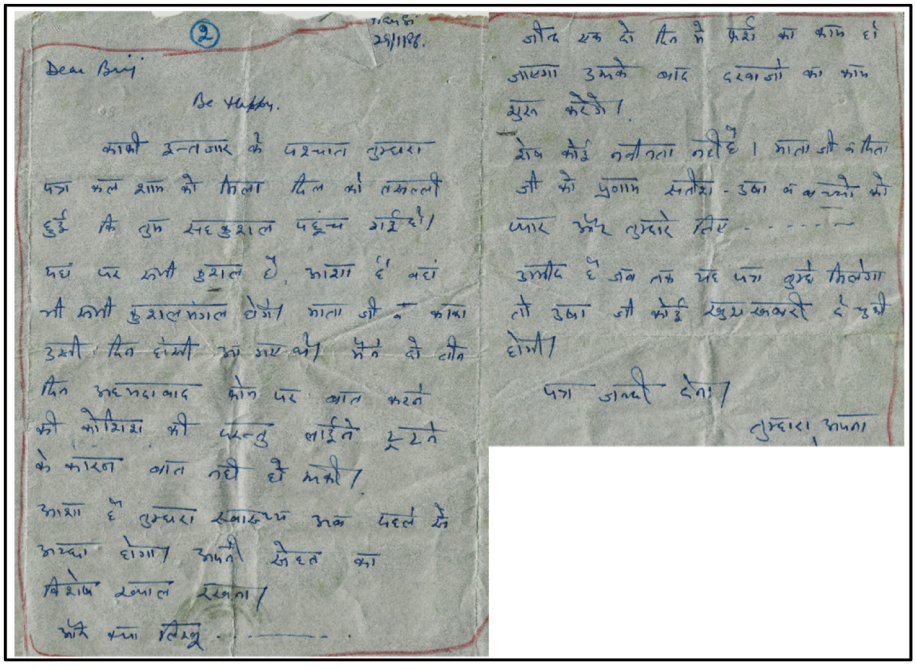

Fig. 8. Handwriting samples of patient collected pre-stroke marked as B-2 belonging to year 1986.

5. Discussion

5.1. General characteristics and lack of individuality in post-stroke writings

As illustrated in Table-1, perusal of the post-stroke writings marked A-1 to A-4 exhibits remarkable consistency in general characteristics of movement, skill, line-quality, speed, pen control, letter size, and letter combinations; which are characteristically different from those of the pre-stroke writings. All these characteristics are symptoms of under developed, graphically immature writings, resembling a naïve school child. The apparent lack of mental capacity to reproduce the pre-stroke master patterns from the past memory is consistent with the findings of Maeshima that inability to acquire or accumulate new memories after the episode of stroke (i.e., anterograde amnesia) and failure to recall memory acquired before the stroke (i.e., retrograde amnesia) are the usual symptoms of memory impairment in stroke patients [27]. Thus, forensic evidence of the case is duly supported by neuroscience studies. Harrison too emphasized on difficulties in identification of under-developed writings for want of individuality [26].

Hence result of the study, that the post-stroke writings lack individuality needed for their identification, is appropriately justified in

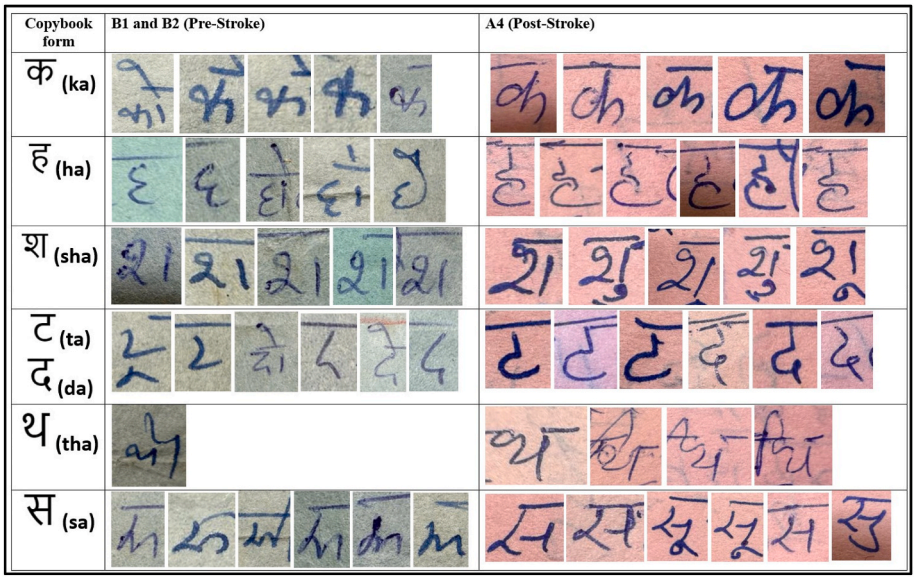

Fig. 9. Juxtaposed comparison chart of dissimilarities between pre-stroke and post-stroke handwritings of the patient.

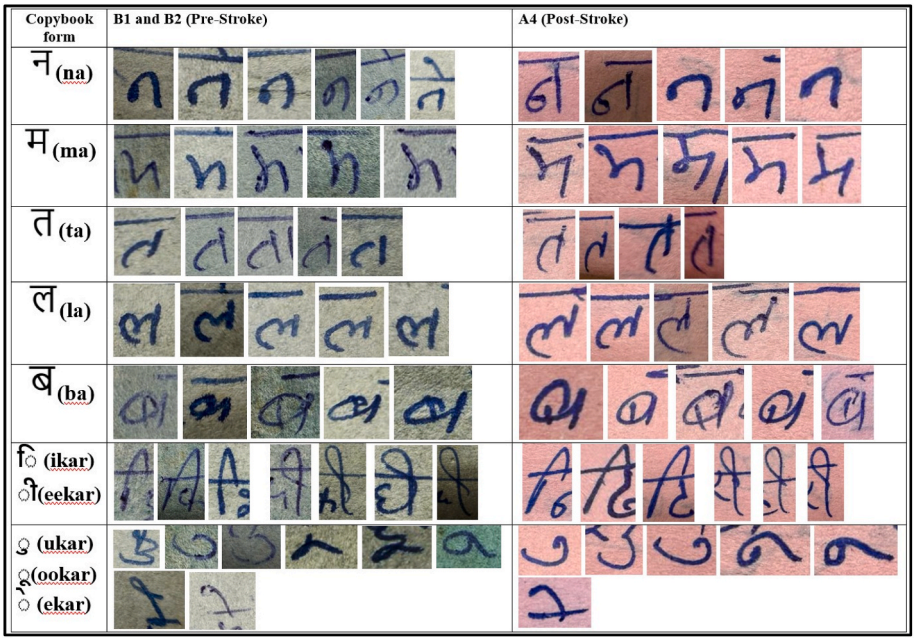

Fig. 10. Juxtaposed comparison chart of similarities between pre-stroke and post-stroke handwritings of the patient.

view of the facts and circumstances of the case.

5.2. Likelihood of different authorship

Forensic examination reveals that the post-stroke writings exhibit a number of dissimilarities in general and in non-general features, in addition to a few similarities of letter-forms and vowel signs, vis-à-vis the pre-stroke writings. However, the similarities don't appear to be too significant and sufficient to indicate common authorship, whereas, dissimilarities which are apparently fundamental to the structure of handwriting, seem to outweigh them, as being under-developed writings, they are not reliable indicator of common authorship. These observations are consistent with the views expressed by Hilton that, in handwriting authorship related document problems, even a limited number of basic differences, against numerous strong similarities, are controlling and accurately establish non-identity [28].

Hence, in view of the forensic evaluation duly supported by the subject authorities, the result of study, that the possibility of different authorship appears to be much more likely than that of their common authorship, is justifiable.

5.3. Justification for the possibility of common authorship

For an accurate identification, thorough evaluation of all the similarities, dissimilarities, and the unexplained features, if any, vis-à-vis the conditions and circumstances surrounding the writer and the writing process, is absolutely necessary. Further, the FDE is also required to differentiate between the inter-writer and intra-writer variations before treating any dissimilarity as fundamental difference. It has also been described that, various conditions contribute to handwriting dissimilarities, which inter-alia, includes the physical and/or mental condition of the writer [25]. Apparently, the reasons for numerous dissimilarities

Table-1
Comparative study of general writing characteristics.

S. No.	Characteristic studied	Set-2 (B1-B2)	Set-1 (A1-A4)
1	**Period of execution**	1982, 1986	2003–2006
2	**Movement**	Wrist predominant	Finger predominant
3	**Skill**	Above average (Good)	Much below average (Poor)
4	**Line Quality**	Free, smooth & normal	Lacks freedom & smoothness
5	**Speed**	Reasonably fast & carefree	Extraordinarily slow & careful
6	**Pen Control**	Strong and well-coordinated	Extraordinarily Weak and considerably poor
7	**Letter size**	Normal and uniform	Predominantly larger
8	**Letter combinations**	Mostly present	Conspicuously absent

Table-2
Dissimilarities and similarities in letter-specific characteristics of pre-stroke and post-stroke handwritings.

Sr. No.	Dissimilarities	Similarities
1	In the writings marked B1 and B2 of the set-2, direction of movement of the latter 'Ka' at several places is such that the letter commences with the formation of vertical staff followed by the leftward oval, whereas, that of the writings marked A4 of set-1is observed in the reverse order.	Nature of commencement of initial part of the letter 'Na' as found in A4, B1 and B2.
2	In the writings marked B1 and B2 of the set-2, the Hindi letter 'Ha' has been speedily formed in single operation of movement, whereas that of the writings marked A4 in set-1 has been slowly and carefully executed in multiple pen operations.	Blind commencement of the letter 'Ma' as found in A4, B1 and B2.
3	Nature and location of start and finish of Hindi letter 'Sha' as found in A4 differs from that in B1 and B2.	Nature and location of finish of the letter 'Ta' as found in A4, B1 and B2.
4	Vertically downward commencement of the letters 'Ta' and 'Da' as found in A4 is nowhere found as such in B1 and B2.	Nature of vertical staff and leftward curved strokes of the letter 'La' as found in A4, B1 and B2.
5	Manner of execution of letter 'Tha' as found in A4 with nature of its commencing oval, its body and final vertical staff is found to differ from that in B2.	The direction of movement of the letter 'Ba' as found in A4, B1 and B2.
6	Manner of execution of the letter 'Sa' in A4 which completely differs from that in B1 and B2.	Similar execution of the vowel-signs representing 'ikar', 'eekar', 'ukar', 'ookar' and 'ekar', though with restricted speed, freedom and fluency, in A4, B1 & B2.

needed to be thoroughly investigated. It has also been stated that the specimen and/or questioned writings may not accurately reflect the writer's usual behaviour due to factors such as nonrepresentative sampling over time, altered neurophysiology, intentional modifications, and changes in environmental conditions [29]. Obviously, intra-writer variability due to mental health of the writer as a possible reason for numerous dissimilarities needed to be ruled out before treating them as fundamental to the structure of handwriting. Hence, the weightage of similarities of letter-forms, howsoever under-developed, insignificant or insufficient they may appear to be, cannot be underestimated, especially because the actual reason for the numerous dissimilarities could be the wider range of intra-writer variability, rather than different authorship.

Hence, result of the study, that despite the lack of significant & sufficient similarities, the possibility of common authorship, howsoever remote, cannot be ruled out is justifiable, in view of the forensic evaluation duly supported by the subject authorities.

5.4. Inconclusive findings

As already stated, the post-stroke writings, being under-developed, lack individuality needed for their identification. Hence, the apparent similarities between the post and pre-stroke writings cannot be said to be habitual, and consequently, their overall significance in identification is minimal. Further, collective significance of the numerous dissimilarities, cannot conclusively indicate different authorship, because the other (i.e., invisible) reasons for such dissimilarities, could not be ruled out, in totality. Therefore, the suggestion made by Ellen that, if the evidence is found to be sufficient either way (i.e., for a positive or negative opinion), the same may be reported accordingly [30], otherwise, no conclusion may be expressed, is worth consideration in this case.

Hence, result of the study, that no definite opinion could be expressed regarding the common authorship or otherwise on the basis of material supplied, is justifiable, in view of the forensic evaluation duly supported by the subject authorities.

5.5. Necessity for contemporaneous standards

Mohammed stated that contemporaneous specimens are all the more significant and relevant in any case of handwriting authorship especially involving old age, illness, injury or other physiological issues, wherein the FDE's must observe utmost caution to avoid error [8]. Such standards become necessary for examination because, as stated by Harralson and Miller handwriting goes on changing progressively over the lifetime of the writer and, the nature and extent of variability is specific to the writer and the conditions and circumstances surrounding that writer at a given point of time [25]. Accordingly, the required time frame of contemporaneity also varies from case to case depending upon the extent and range of intra-writer variations. Koppenhaver, stated that documents executed around 2–3 years of the date of the questioned document are generally acceptable as contemporaneous standards unless there has been a major change in physical and mental condition of the writer, in which case a shorter time period would be necessary [31]. However, as stated by Osborn, to be more precise, contemporaneity is to be measured not only in terms of years, but also considering the health condition (i.e., physical and mental) of the writer [32]. Obviously, if the health condition is continuously deteriorating, such as during the moribund period, the time frame of contemporaneity must include the comparison standards of that period. Reverting to the present case, there is almost 20-year gap between the execution of pre- and post-stroke writings, which could have changed the writing characteristics materially to such an extent as to make the writing unrecognizable, thereby rendering all the previous standards as unfit for comparison. However, ultimately, it would be for the expert concerned to voice his conclusion as to whether the disputed handwriting/signature and the admitted handwriting/signature are capable of comparison, for a viable expert opinion [33].

Further, it has been generally considered that contextual information and case history that is sometimes mentioned in the request letter for examination has the potential to bias the examiner and consequently affect the results of examination, whereas most of the FDEs are of the opinion that some vital information about the age and health condition of the writer, especially the state of his physical and mental health at a given point of time becomes necessary to be provided in some of the cases for correct evaluation and interpretation of handwriting characteristics. In this connection, the viewpoint of the FDE's was consistent with the statement of Osborn, that certain general qualities in handwriting necessarily are affected by conditions of the writer or surrounding the writer and often it becomes necessary to corelate the written result with the alleged conditions [32]. As such, clinical and

medical history of the concerned writer undoubtedly constitutes such an indispensable information, the non-disclosure of which may be counter-productive and lead to involuntary miscarriage of justice. In the present case also, had the examiner taken a decision regarding authorship of the post-stroke writings, ignoring the medical history, there was likelihood of an involuntary false negative opinion being expressed by the examiner. Therefore, in consideration of facts and circumstances and the views expressed by the subject authorities, re-examination of the case with true contemporaneous standards appeared to be the most viable option.

Hence, there is enough justification for the result of the study mentioned at number 5 above that contemporaneous pre-stroke writings (i.e., for the period 1986–2003) as well as clinical & medical history of the subject needs to be examined before attempting either to link, or to rule out, the possibility of the subject being the author of the post-stroke writings.

6. Limitations

Some limitations that were inherent to the case study are stated as under.

6.1. Absence of extensive pre- and post-stroke data

The analysis of the study is constrained by the scarcity of detailed information regarding the writer's heath before and after the stroke. Determining the precise effect of stroke on handwriting is difficult due to lack of contemporaneous data.

6.2. Impact of external factors

The handwriting changes observed in the post-stroke samples may have been caused by various external factors, including aging, medication, rehabilitation therapies, and other health conditions. These factors were not fully controlled or accounted for in the study.

6.3. Limited sample and temporal gap

The small sample size and significant temporal gap between the pre- and post-stroke samples also poses challenge. The time gap introduces additional variables, like natural changes in handwriting over time, which could affect the analysis.

6.4. Generalization of findings

Findings of this particular case study may not be generalizable to other such cases. Each stroke-induced memory impairment case is unique in itself, and its impact on handwriting as well as other motor activities may also vary widely from person to person. Further studies covering varying types of stroke patients by a collaborative team of document examiners and medical professionals will certainly enhance the utility of this study.

Despite the above limitations, the study provides a fundamental perspective on stroke induced handwriting variability, paving the way for more extensive research.

7. Conclusion

Due to memory impairment, identification of post-stroke writing, in comparison with the pre-stroke specimens, is certainly a grey area in forensic document examination, where, the FDE's must proceed with extreme caution. Hence, in the context of handwriting, the principle of contemporaneity must be applied strictly, meticulously and minutely so as to include comparison specimens pertaining to the period, just before and after, the occurrence of the event affecting handwriting, within its time frame. The suggestion stands vindicated in the light of statement made by Harrison that, in the event of serious illness, a signature can suddenly undergo an unexpected change and if the questioned 'will' pertains to a moribund period, examination of standard signatures covering this period also becomes essential for an accurate opinion regarding its authorship or otherwise [26]. It is also advisable to insist upon the authentic clinical and medical history of the writer to confirm and corelate the alleged medical condition with the forensic observations. Further, unless all the prerequisites are appropriately considered and evaluated, definite opinions, indicating common or different authorship, should be avoided in such cases. The study also highlights the need for further research in such cases and to review and modify some of the principles and practices of forensic document examination to meet such challenges in future in view of NIST recommendations 2.1, 2.2 and 2.3 [34].

CRediT authorship contribution statement

Mohinder Singh: Writing – original draft, Validation, Methodology, Investigation. **Romika Chopra:** Writing – original draft, Validation, Methodology. **Ajay Sharma:** Methodology, Investigation, Data curation. **Vishal Sharma:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

All the authors declare that there is no any financial, personal, or professional affiliation that may be perceived as potential sources of bias or conflict of interest.

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