Age-related changes in executive control and their relationships with activity performance in handwriting

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ABSTRACT

Deterioration in the frontal and prefrontal cortex associated with executive functions (EF) occurs with age and may be associated with changes in daily performance. The aim of the present study was to describe changes occurring with age in Executive Functions (EF) and handwriting activity, as well as to analyze relationships between age, EF and handwriting performance. The study population included 80 healthy participants (aged 31 to 76+) living in the community. After answering five questions about their writing habits, the participants completed the Behavioral Assessment of the Dysexecutive Syndrome (BADS). In addition, they performed a handwriting task on a digitizer included in the Computerized Penmanship Evaluation Tool (ComPET), which provides kinematic measures of the handwriting process. Significant differences were found between the four age groups for both EF and temporal and spatial handwriting measures. A series of regressions indicated that age predicted 35% of the variance of the BADS profile score (EF control) and 32% of the variance of in-air time while writing. The results of this study indicated age effect on both EF control and handwriting performance. Possible implications for further research and clinical evaluation and intervention are discussed.

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1. Introduction

Aging involves neurodegenerative changes, including anatomical, physiological, and chemical changes that occur in the brain (Treitz, Heyder, & Daum, 2007). Specifically, deterioration occurs in the frontal and prefrontal cortex, which are the main brain areas related to Executive Functions (Amieva, Phillips, & Della Sala, 2003; Lin, Chan, Zheng, Yang, & Wang, 2007). Executive Function (EF) is an umbrella term that encompasses high-level cognitive functions required for the performance of complex everyday activities, such as planning and organization, reasoning and problem solving, conceptual thought, self-correction and judgment, and decision making (Burgess et al., 2006; Norris & Tate, 2000; Ylvisaker & Feeney, 2002).

Despite the importance of evaluating executive function and its impact on real human performance (Baum, Foster, & Wolf, 2009), the pattern and course of age effects on EF is inconclusive (Treitz et al., 2007). Studies have demonstrated a decrease in general executive functions with age, which harms working memory, planning, and imitation in particular (Gazzaley, Cooney, Rissman, & D’Esposito, 2005; Jennings, Dagenbach, Engle, & Funke, 2007; Lin et al., 2007; Treitz et al., 2007). However, the ability to understand the impact of the decrease in EF on everyday functioning in a variety of situations is limited (Baum et al., 2009).

The question of how to best evaluate EF deficits while creating a functional real-world task needs to be considered in light of the complexity of this domain (Isquith, Gioia, & Espy, 2005). In this context, the ecological validity of measuring EF refers to the conditions under which generalizations can be made from controlled experiments to natural real-life scenarios (Norris & Tate, 2000; Tupper & Ciccone, 1990). In order to address the need for a tool that simulates real life, EF deficits were evaluated in the present study by the Behavioral Assessment of the Dysexecutive Syndrome (BADS) test battery (Wilson, Alderman, Burgess, Emsile, & Evans, 1996). Unlike other neuropsychological tests that focus on specific component/s of EF (e.g., inhibition, attention, working memory, etc.), this standardized test evaluates executive functions as a whole. The test simulates the complex multifactorial nature of everyday functioning by requesting the performance of six complex tasks requiring the integration of executive functions (Jovanovski, Zakzanis, Young, & Campbell, 2007). These tasks require cognitive flexibility, problem solving and development of a plan for action, planning, judgment and temporal estimation, as well as behavioral regulation (Norris & Tate, 2000; Wilson et al., 1996). An EF profile is achieved based on the performance scores of the six tasks.

Besides using an ecologically valid test, such as the BADS, for the evaluation of EF deficits, it is recommended that a performance-based measure of functioning, such as the ability to write one’s name, be employed as well in order to gain better insight into the deterioration in EF and its impact on real-world daily performance (Hooren et al., 2007; Suthers & Seeman, 2004). Slavin, Phillips, Bradshaw, Hall, and Presnall (1999) have indicated that handwriting may be utilized as part of neuropsychological testing, given that it is a sensitive task which can be subjected to kinematic analysis (Slavin et al., 1999).

In keeping with this line of thought, the focus of the present study is on the ‘transcription phase’ which is considered as the ‘lower level’ of writing production (Berninger & Swanson, 1994). The transcription draws on the processes involved in retrieving letterforms and familiar word spellings from long-term memory, strategically spelling novel words, and motor planning to produce the letters by hand. Such an approach differs from focusing on the generation of written content and ideas which is considered as ‘higher level’ of the writing performance (Berninger & Swanson, 1994).

Although the transcription phase is considered as the lower level of writing production, there is evidence in the literature to its complexity. Based on several handwriting models (e.g., Denckla & Roeltgen, 1992; Ellis, 1982; Graham, Struck, Santoro, & Berninger, 2006; van Galen, 1991), handwriting transcription can be depicted as a hierarchically organized representation of mental motor movements. The premise of these models is that handwriting occurs because of distinct processing activities whereby the output from an earlier stage forms the input for the next stage. For example, according to van Galen’s model, the writer first activates a lexical process which provides abstract graphemic representations, those graphemic representations are being translated into alographic code stored in a short term motor buffer which retrieves and releases the different motor programs.

required for letter writing. The parameters for executing the motor program (e.g., letter size) are then set, followed by neuromuscular instructions that specify the exact muscles and amount of force required for producing the letter. Other researchers added that in fact this production ends with the process of deciding where to place the letter on the page (in relation to baseline and to other letters) (Denckla & Roeltgen, 1992; Graham et al., 2006).

Those models manifest that in fact the transcription phase is complex by itself and requires varied EF components as working memory (for representing and saving visual images in memory) as well as organization in space and time abilities. Further support for the involvement of EF in the transcription phase was documented. Engle (2002) remarked the need for the “ability to control attention (and avoid distraction) to maintain information in an active, quickly retrievable state” in such performance as handwriting transcription. Other researchers also reinforce the act of the involvement of EF components as decision making, intentional control, planning in time and space (Meltzer, 2007), revising behavior (De La Paz & Graham, 1977), and organization (Mercer, 2005; Tseng & Cermak, 1993) in the transcription process.

Most previous studies about the relationships between EF and writing were focused on the written content/ideas following the definition of EF as control processes that influence one’s overall written output (Hooper, Swartz, Wakely, De Kruif, & Montgomery, 2002). However, research on the transcription phase among adults has been neglected (Connelly, Campbell, MacLean, & Barnes, 2006; Peverly, 2006) and literature about possible relationships between the decline in EF and writing production in the ‘transcription phase’ is scarce.

In that context, relationships between one component of EF – Working Memory (WM) and text generation were analyzed by Hoskyn and Swanson (2003). The researchers found that WM scores account for a significance variance in age-related influence on the transcription process (handwriting speed and spelling). Their results supported previous studies that show WM is associated with complex components of text generation (McCutchen, 2000). They remarked that the WM measures provide a measure of storage capacity for a wide variety of tasks as required in the handwriting process.

Recent developments in data collection technology enable an examination of the writing process, rather than the written product. With the aid of a digitizing tablet and an instrumented pen, the researcher can now monitor handwriting in real time and store it in a format amenable to sophisticated kinematic temporal and spatial measures (Rosenblum, Parush, & Weiss, 2003a; Slavin et al., 1999). These measures may be indicators for EF decline, including planning and organization in space and time, when a hierarchical complex activity such as handwriting is being performed.

Despite the importance of handwriting in everyday life (Mercer, 2005), only a few studies have shown deterioration in handwriting performance in the elderly, as manifested in objective measures of the handwriting process (e.g., Dixon, Kurzman, & Friesen, 1993; Rosenblum & Werner, 2005). Although some previous studies have explored the relationship between EF and writing performance among elderly people, the focus has been on a specific EF component, such as working memory (e.g., Hoskyn & Swanson, 2003). To the best of our knowledge, no study has considered EF as a whole construct, as reflected through task performance (BADS). Furthermore, none of the studies conducted have measured handwriting transcription (and not writing content) with objective spatial and temporal measures.

Hence, the goal of this study was to refine our understanding of the decrease in EF deficits in the elderly, as manifested in objective measures of the handwriting process (e.g., Dixon, Kurzman, & Friesen, 1993; Rosenblum & Werner, 2005). Although some previous studies have explored the relationship between EF and writing performance among elderly people, the focus has been on a specific EF component, such as working memory (e.g., Hoskyn & Swanson, 2003). To the best of our knowledge, no study has considered EF as a whole construct, as reflected through task performance (BADS). Furthermore, none of the studies conducted have measured handwriting transcription (and not writing content) with objective spatial and temporal measures.

Hence, the goal of this study was to refine our understanding of the decrease in EF deficits in the elderly, as manifested in objective measures of the handwriting process, and to identify the relationships between EF control and actual performance in handwriting, using kinematic spatial and temporal performance-based measures. The four main hypotheses of the present study were as follows:

1. Significant differences will be found between the various age groups in:
   a. EF control as evaluated by the BADS test.
   b. Temporal and spatial measures of the handwriting process, as evaluated by a computerized system (ComPET).
2. Executive control would be predicted by age.
3. Certain handwriting performance measures will be predicted by age.
4. Executive control will add further value to the prediction of handwriting performance ability, beyond age.
2. Methods

2.1. Participants

Participants included 80 healthy and independently functioning people living in the community. All participants had been living in Israel for at least 20 years, were proficient in Hebrew (speaking, reading and writing), had at least 12 years of education (\(M = 15.20; \ SD = 2.93\)), were right-handed, and had normal vision and hearing ability (with or without accessories). Participants who reported suffering from a neurological disease or arthritis that found expression in their upper extremity function were not included in the study.

An initial screening revealed that all the participants had sufficient cognitive status and no symptoms of depression or memory deficits. The participants’ cognitive status was evaluated by the Hebrew version of the Mini Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975; Werner, Heinik, Mendel, Raikher, & Bleich, 1999), with scores ranging from 0 (total cognitive deterioration) to 30 (normal cognitive functioning). In accordance with the reported cut-off score of 24 in the literature (Tangalos, Smith, & Ivnik, 1996), three participants scoring less than 24 were excluded from the study. The participants’ mean score on the MMSE was 29.31 (SD = 0.82).

The Geriatric Depression Scale (GDS) was administered in order to rule out depression. The participants’ mean score was 1.38 (SD = 1.52), with depression indicated by scores of 12–15 (Yesavage et al., 1983). Participants’ memory abilities were evaluated using the Subjective Memory Scale (Derouesne, Lacomblez, Thibault, & LePoncin, 1999), which includes six items rated on a scale ranging from 0 (not at all) to 2 (all the time). The participants’ mean score was .41 (SD = 0.22).

The participants (N = 80) were divided into four groups according to age: 31–45, 46–60, 61–75, 76+. Each group included 20 subjects, with an equal distribution of males and females. As presented in Table A1, no significant differences were found between the four groups in their cognitive status and subjective memory. Significant differences were found between the four groups in years of education.

2.2. Instruments

Handwriting-background characteristics: Participants were asked four questions to characterize their writing performance. The first question was about writing frequency (4. every day; 3. often; 2. sometimes; 1. hardly ever). The other three questions assessed the participants’ writing behavior: whether they have difficulty writing (1. all the time; 2. often; 3. rarely; 4. never), whether they get tired, and whether they avoid writing (1. Yes; 2. No).

Digitizing tablet and online data collection and analysis software: An online computerized handwriting evaluation, called ComPET – Computerized Penmanship Evaluation Tool (previously referred to as POET; Rosenblum, Parush, & Weiss, 2003b) was used to administer the stimuli and to collect and analyze the data. The ComPET was developed in response to the absence of a quantitative, objective handwriting evaluation for the Hebrew language, but is currently suitable for use with all languages.

### Table A1
Participants’ background characteristics.

<table>
<thead>
<tr>
<th></th>
<th>1 31–45 n = 20 M (SD)</th>
<th>2 46–60 n = 20 M (SD)</th>
<th>3 61–75 n = 20 M (SD)</th>
<th>4 76+ n = 20 M (SD)</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>38.19 (4.73)</td>
<td>52.82 (4.43)</td>
<td>68.13 (4.80)</td>
<td>81.70 (5.03)</td>
<td>313.37</td>
<td>.00</td>
</tr>
<tr>
<td>Years of education</td>
<td>16.05 (3.18)</td>
<td>15.90 (2.77)</td>
<td>15.20 (2.82)</td>
<td>13.65 (2.49)</td>
<td>3.01</td>
<td>.03</td>
</tr>
<tr>
<td>MMSE</td>
<td>29.65 (.59)</td>
<td>29.45 (.69)</td>
<td>29.15 (.81)</td>
<td>29.00 (1.02)</td>
<td>2.7</td>
<td>.05</td>
</tr>
<tr>
<td>GDS</td>
<td>.95 (1.23)</td>
<td>1.15 (1.75)</td>
<td>1.45 (1.54)</td>
<td>1.95 (1.47)</td>
<td>1.66</td>
<td>.18</td>
</tr>
<tr>
<td>Subjective Memory Test</td>
<td>.36 (.22)</td>
<td>.45 (.23)</td>
<td>.42 (.20)</td>
<td>.42 (.26)</td>
<td>.52</td>
<td>.66</td>
</tr>
</tbody>
</table>

Note: MMSE – Mini Mental State Examination; GDS – Geriatric Depression Scale.

tool includes two main parts: 1) data collection, which is language-independent and easy to use for handwriting tasks; and 2) data analysis, which has been programmed via MATLAB software toolkits. The data collection part was designed to be as user-friendly as possible so as to enable its application by clinicians and researchers in their everyday practice.

Participants were requested to copy a paragraph (as presented in Fig. A1) which was printed on a piece of paper in manuscript Hebrew font (Gutman Yad Brush) size 20 and was placed in front of them on the table.

The present study focused on writing tasks in Hebrew. As presented in Fig. A1, not unlike Latin language writing, each word and each letter are written separately with no connections between letters. In order to demonstrate it, the first four words are signed in Fig. A1 with above lines. Furthermore, some letters in the Hebrew alphabet are constructed from two separate, unconnected components or strokes. For example, as demonstrated in Fig. A1, the first word includes 3 letters, of them, the first and the third letter (HEY), (signed by underlines) is formed each by two separate components.

The writing task was performed on A4 lined paper affixed to the surface of a WACOM Intuos 2 [model GD 0912-12X18] x-y digitizing tablet, using a wireless electronic inking pen [Model GP-110]. Displacement, pressure and pen tip angle were sampled at 100 Hz via a 1300 MHz Pentium (R) M laptop computer. The computerized system enables the collection of spatial, temporal, and pressure data while the subject is writing. The digitizer gives an accurate temporal measure for the writing performance, both when the pen is touching the tablet and when it is in the air. It gives an accurate spatial measure when the pen is touching the tablet and/or when it is lifted up to 6 mm above the digitizer. Beyond 6 mm, the spatial measurement is not reliable (manifested as straight gray lines, as appears in Fig. A2,3), but the temporal measurement remains so. Participants were requested to copy a paragraph containing 47 words with 170 letters, a task which provides the opportunity to evaluate prolonged writing performance (see Fig. A1).

Kinematic measure: Based on previous results (Rosenblum & Werner, 2005; Werner, Rosenblum, Bar-On, Heinik, & Korczyn, 2006), we focused on temporal and spatial measures per written stroke.

Temporal measures:

1. The mean stroke on-paper performance time in seconds. On-paper time is defined as the mean time of pen trajectories during writing when the pen is in contact with the writing surface, starting from the point at which it touches the paper to the point at which it is no longer touching the paper. 'Touching the paper' refers to a pressure level above 50 units.
2. The mean stroke in-air performance time in seconds. In-air time is defined as the mean time of pen trajectories during writing when the pen is not in contact with the writing surface (i.e., when the pressure is under 50 in non-scaled pressure units) while passing from one letter/word to the other. In effect, it is the time of ‘non-writing’ while writing.

Fig. A1. The paragraph copying task, as illustrated below, is placed in front of the participant. Note: The lines above the first four words and below the first and third letter were added in this manuscript to demonstrate the act of Hebrew writing.
3. The ratio between on-paper and in-air time per stroke was calculated for the entire task.

Furthermore, three representative spatial characteristics supplied by ComPET were analyzed, per strokes written on the paper:

1. The mean stroke width in centimeters (i.e., the whole stroke width on the x-axis).
2. The mean stroke height in centimeters (i.e., the whole stroke height on the y-axis).
3. The mean stroke length in centimeters (i.e. the total path length of the pen’s trajectory from the point at which it touches the paper until the point at which it leaves the paper).

The Behavioral Assessment of the Dysexecutive Syndrome (BADS) (Wilson et al., 1996). This is a reliable, valid tool designed to predict everyday problems arising from the Dysexecutive Syndrome. The tool’s concurrent validity with other standard neuropsychological tools of executive abilities has been demonstrated (Norris & Tate, 2000). The BADS was translated into Hebrew and found suitable for the Israeli population (Dvir et al., 2003).

The instrument consists of six subtests and a self-report (or caregiver) questionnaire. The profile score for each subtest ranges from 0 to 4, and the total profile score ranges from 0 to 24. A higher profile score indicates better functioning. Following is a short description of the BADS subtests (Wilson et al., 1996):

1. Rule Shift Card – Assesses the participant’s ability to respond correctly to a rule and to shift from a simple to a complex rule. The time taken and number of performance errors are recorded.
2. Action Program Test – Assesses the ability to devise and implement a solution to a practical problem, such as removing a cork from a narrow plastic tube, without contravening a set of rules. The score is based on the number of steps completed without assistance.
3. Key Search Test – Assesses the ability to plan a strategy to solve a problem, as demonstrated by drawing a route on a piece of paper indicating how to find a key lost in a field. The score is based on a number of criteria, including whether the rater believes the strategy to be systematic, efficient, and likely to be effective.
4. Temporal Judgment Test – Assesses judgment and abstract thinking based on common knowledge, as reflected by the ability to estimate times for everyday events. The score is based on the accuracy of the estimates.
5. Zoo Map Test – Assesses the ability to formulate and implement a plan independently and to follow a pre-formulated plan, as illustrated by plotting or following a route with a pen through a map drawn on a paper. The score is based on the successful implementation of the plan and composed of the planning time, execution time and performance quality.
6. Modified Six Elements Test – Assesses time management ability by dividing the available time between a number of simple tasks, such as picture naming, arithmetic and dictation, without contravening a set of rules. The score is based on the number of tasks attempted.

2.3. Procedure

After receiving the approval of the Ethics Committee of the University of Haifa, participants were selected by convenience sampling and were requested to sign an informed consent form. Potential participants were asked five questions about their general health. Those who met the criteria were then screened with the MMSE and GDS tests, as well as the subjective memory questionnaire. The 80 people found to be suitable were asked about their writing performance and evaluated by the BADS and ComPET. All participants were examined in similar environmental conditions, in a quiet room with a comfortable chair and table. The participants were asked to write as they usually do every day.

2.4. Data analysis

Descriptive statistics were used to describe the sample and the main variables. The differences between the groups on the EF profile score and on the performance time ratio were analyzed by ANCOVA, with years of education serving as the covariate.

A multivariate analysis of covariance (MANCOVA), with group membership serving as the independent variable and years of education as the covariate, was used to examine group differences across: 1) the dependent variables of the six BADS subtests; 2) the temporal handwriting performance measures per written stroke (i.e., on-paper and in-air time); and 3) the spatial handwriting performance measures per written stroke (i.e., stroke height, width, and length).

Finally, series of hierarchical regression analyses were applied in order to determine whether age predicts executive control and handwriting performance, and whether executive control adds further value to the prediction of handwriting performance beyond age.

3. Results

The distribution of writing performance: among the age groups is presented in Table B1. At least 90% of the participants in the three younger groups reported writing often or every day, as compared to only 75% in the older group, and over 20% reported writing sometimes. According to this self-report questionnaire, the majority (90%) in each group did not find handwriting activities difficult and did not avoid writing.

Hypothesis 1a: Significant differences will be found between the various age groups in EF control as evaluated by the BADS test.

As presented in Table C1, the ANCOVA yielded significant differences between the four groups on the BADS profile score. Furthermore, the MANCOVA for all six subtests indicated significant differences between the groups ($F(18,201) = 3.13, p < .001, \eta^2 = .21$), revealing a gradual decrease with age. A post-hoc test emphasizes the significant differences between the older group (76+) and the two younger groups.

Hypothesis 1b: Significant differences will be found between the various age groups in temporal and spatial measures of the handwriting process, as evaluated by a computerized system (ComPET).

An initial examination of the written products indicated that all participants copied the whole paragraph, including the same number of letters and words, with no spelling mistakes. Furthermore, there were no significant differences between the groups in the number of written strokes.

As presented in Table D1, the MANCOVA analysis on the temporal measures (i.e., on-paper and in-air time) indicated significant differences between the groups ($F(6,148) = 7.89, p < .0001, \eta^2 = .24$).

<table>
<thead>
<tr>
<th>Table B1</th>
<th>Distribution of the responses for using writing in everyday life according to age groups, by percentage.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 31–45 n = 20 (%)</td>
</tr>
<tr>
<td>How often do you write? (any type of writing)</td>
<td></td>
</tr>
<tr>
<td>Everyday</td>
<td>70</td>
</tr>
<tr>
<td>Often</td>
<td>20</td>
</tr>
<tr>
<td>Sometimes</td>
<td>5</td>
</tr>
<tr>
<td>Hardly ever</td>
<td>0</td>
</tr>
<tr>
<td>Do you have difficulty while writing?</td>
<td>All the time</td>
</tr>
<tr>
<td>Never</td>
<td>90</td>
</tr>
<tr>
<td>Sometimes</td>
<td>10</td>
</tr>
<tr>
<td>Do you avoid writing?</td>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
<td>100</td>
</tr>
<tr>
<td>Do you get tired while writing?</td>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
<td>95</td>
</tr>
</tbody>
</table>

The ANCOVA analysis also indicated significant differences between the groups for the time ratio ($F(3.75) = 5.66, \ p = .001, \ \eta^2 = .18$). While the association between on-paper and in-air time for the younger group was 140%, it increased to 200% in the older group (76+).

A similar trend was found for the spatial measures (i.e., height, width, and length per stroke), with the MANCOVA analysis indicating significant differences between the groups ($F(12,190) = 3.94, \ p < .001, \ \eta^2 = .18$). Both temporal and spatial measures were found to increase with age.

Table C1
Means, standard deviations, $F$ Scores, $\eta^2$ and post hoc results for the BADS profile score and the six subtest scores.

<table>
<thead>
<tr>
<th>Age group</th>
<th>1 (31–45 n = 20 M)</th>
<th>2 (46–60 n = 20 M)</th>
<th>3 (61–75 n = 20 M)</th>
<th>4 (76+ n = 20 M)</th>
<th>$F(3,80)$</th>
<th>$\eta^2$</th>
<th>Post hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BADS profile score</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(range from 0–24)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Rule shift card</td>
<td>3.90 (.31)</td>
<td>3.90 (.45)</td>
<td>3.45 (.76)</td>
<td>3.25 (.79)</td>
<td>5.77**</td>
<td>.18</td>
<td>4 &lt; 1, 2</td>
</tr>
<tr>
<td>2. Action program</td>
<td>4.00 (.00)</td>
<td>3.75 (.55)</td>
<td>3.40 (.75)</td>
<td>2.95 (.83)</td>
<td>10.69**</td>
<td>.29</td>
<td>3, 4 &lt; 1</td>
</tr>
<tr>
<td>3. Key search</td>
<td>3.50 (.76)</td>
<td>2.75 (1.02)</td>
<td>2.35 (1.09)</td>
<td>2.00 (1.17)</td>
<td>7.95</td>
<td>.24</td>
<td>4 &lt; 2</td>
</tr>
<tr>
<td>4. Temporal judgments</td>
<td>3.25 (.79)</td>
<td>3.00 (.97)</td>
<td>2.95 (.76)</td>
<td>2.45 (.94)</td>
<td>2.96**</td>
<td>.10</td>
<td>3, 4 &lt; 1</td>
</tr>
<tr>
<td>5. Zoo map</td>
<td>3.25 (.79)</td>
<td>3.00 (.97)</td>
<td>2.30 (1.21)</td>
<td>2.25 (.72)</td>
<td>5.65*</td>
<td>.18</td>
<td>4 &lt; 1</td>
</tr>
<tr>
<td>6. Modifies six elements</td>
<td>3.70 (.57)</td>
<td>3.35 (.74)</td>
<td>3.30 (.73)</td>
<td>2.90 (.91)</td>
<td>2.88</td>
<td>.11</td>
<td>4 &lt; 1</td>
</tr>
</tbody>
</table>

Post hoc: presented for those on which the mean difference is significant at the .05 level.
* $p < .05$.
** $p < .001$.

Table D1
Means, standard deviations, $F$ scores, $\eta^2$ and post hoc results of stroke's temporal and spatial measures of the paragraph copy task (ComPET).

<table>
<thead>
<tr>
<th>Temporal measures (sec)</th>
<th>1 (31–45 n = 20 M)</th>
<th>2 (46–60 n = 20 M)</th>
<th>3 (61–75 n = 20 M)</th>
<th>4 (76+ n = 20 M)</th>
<th>$F(3,80)$</th>
<th>$\eta^2$</th>
<th>Post hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-paper time</td>
<td>.16 (.03)</td>
<td>.17 (.03)</td>
<td>.22 (.04)</td>
<td>.28 (.16)</td>
<td>11.91**</td>
<td>.32</td>
<td>3, 4 &lt; 1, 2</td>
</tr>
<tr>
<td>In-air time</td>
<td>.22 (.08)</td>
<td>.22 (.05)</td>
<td>.38 (.14)</td>
<td>.56 (.23)</td>
<td>18.98**</td>
<td>.43</td>
<td>3, 4 &lt; 1, 2</td>
</tr>
<tr>
<td>In-air/on-paper ratio</td>
<td>1.41 (.55)</td>
<td>1.35 (.37)</td>
<td>1.71 (.52)</td>
<td>2.03 (.52)</td>
<td>4.04*</td>
<td>.14</td>
<td>3, 4 &lt; 1, 2</td>
</tr>
<tr>
<td>Spatial measures per stroke (cm')</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>.22 (.06)</td>
<td>.22 (.04)</td>
<td>.25 (06)</td>
<td>.27 (.08)</td>
<td>3.10*</td>
<td>.11</td>
<td>-</td>
</tr>
<tr>
<td>Height</td>
<td>.34 (.09)</td>
<td>.36 (.07)</td>
<td>.40 (.10)</td>
<td>.46 (.10)</td>
<td>6.13**</td>
<td>.19</td>
<td>4 &lt; 1, 2</td>
</tr>
<tr>
<td>Length</td>
<td>.72 (.20)</td>
<td>.70 (.12)</td>
<td>.80 (.19)</td>
<td>.91 (.22)</td>
<td>4.99*</td>
<td>.16</td>
<td>4 &lt; 1, 2</td>
</tr>
</tbody>
</table>

Post hoc: presented for those on which the mean difference is significant at the .05 level.
* $p < .05$.
** $p < .001$.

The ANCOVA analysis also indicated significant differences between the groups for the time ratio ($F(3.75) = 5.66, \ p = .001, \ \eta^2 = .18$). While the association between on-paper and in-air time for the younger group was 140%, it increased to 200% in the older group (76+).

A similar trend was found for the spatial measures (i.e., height, width, and length per stroke), with the MANCOVA analysis indicating significant differences between the groups ($F(12,190) = 3.94, \ p < .001, \ \eta^2 = .18$). Both temporal and spatial measures were found to increase with age.

![Fig. A2,3](image)
Exhibits an example for typical writing included on-paper (black line) and in-air (gray line) tracks of a 42-year-old (A2) and a 72-year-old (A3), while performing the paragraph copy task.

**Hypothesis 2**: Executive control would be predicted by age.

For the first regression analysis, age was entered as the predictor variable and the BADS profile score (EF control) was entered as the dependent variable.

The results of the regression analyses indicated that, on the whole, years of education ($\beta = .15$) and age ($\beta = -.62$) accounted for 46% of the variance in the BADS profile score ($F(2,77) = 33.27, \ p < .001$) while age contributed for 35% of the variance.
Hypothesis 3: Certain handwriting performance measures will be predicted by age.

An initial examination indicated significant high correlations between mean stroke on-paper and in-air time ($r = .81$, $p < .001$) and between mean stroke width and length ($r = .83$, $p < .001$).

Hence, only in-air time and stroke height and length were entered as dependent variables in series of hierarchical regressions (each measure separately) in order to determine which of those measures would be predicted by age.

The contribution of age beyond the contribution of years of education accounted for each of those handwriting measures found as follows:

The results indicated that age accounted for 6% of the variance of the stroke length ($F(2,77) = 6.65$, $\beta = .26$, $p = .002$), 10% of the variance of stroke height ($F(2,77) = 7.90$, $\beta = .35$, $p < .001$) and 32% of the variance of stroke in-air time ($F(2,77) = 35.39$, $\beta = .59$, $p < .001$).

In light of these results, stroke in-air time was chosen to represent handwriting performance at the following regression analysis.

Hypothesis 4: EF control will add further value to the prediction of handwriting performance ability, beyond age.

A hierarchical regression analysis indicated that years of education ($\beta = -.21$), age ($\beta = .48$) and EF control-(BADS profile score) ($\beta = -.17$) accounted for 49% of the variance in the stroke in-air time ($F(3,76) = 24.85$ $p < .001$). However, the contribution of EF control to the explained variance of stroke in-air time was not significant.
4. Discussion

The present study represents one step in addressing the challenges of understanding the functional characteristics of an increasingly aging population. The relationships between age decline EF deficits and daily life functioning among this population have been examined in most previous studies while using self-report scales (e.g., Amieva et al., 2003; Hooren et al., 2007; Wood et al., 2005). The uniqueness of this study lies in the fact that both EF and handwriting were assessed through actual performance and objective measures of the handwriting process.

An analysis of the participants’ background characteristics highlighted two interesting points. The first point is that the younger age groups have more years of higher education in comparison to the older groups, as previously noted in other studies (e.g., Freedman & Martin, 1999). The second point is that most people (75–90%) are still writing every day despite the prevalence of computer use.

Also in accordance with previous research is the decrease with age in EF control found in the present study (e.g., Fucetola et al., 2000; Pigut et al., 2005). This trend of lower EF abilities among older individuals was found in another study conducted in Israel with 93 participants from three age groups (18–35, 36–50, 51–65), as demonstrated by their lower profile score on the BADS test (Dvir et al., 2003). A similar decrease in EF control was revealed in another study by both the BADS profile score and the six tasks employed in the test to simulate everyday situations, which tap into various executive components (Wilson et al., 1996).

Hence, there is no doubt that a gradual decline in EF occurs with aging. Significant differences were especially evident in the group of participants aged 76+ (group 4), as compared to the younger group (31–45), in the present study for all of the six tasks consistently.

An example of one of those tasks is the Zoo Map Test (task 5). This task requires the ability to formulate and implement a plan independently and to follow a pre-formulated plan. Other studies have reported results similar to those of the present study related to this specific task, with more difficulties (Allain et al., 2005) and slower performance (Salthouse & Siedlecki, 2007) found among elderly adults in comparison to the younger groups.

However, the interesting question is which BADS tasks significantly distinguish between groups which are not in the extreme age range.

Indeed, significant differences were also found in this study for specific tasks, such as action program, key search, and temporal judgment, between the group of participants aged 61–75 (group 3) and younger participants aged 31–45 (group 1). Thus, it would appear that executive control in the areas of planning strategy to solve a problem (key search), implementation of a solution (action program), and time estimation and judgment (temporal judgment) significantly decreases from age 61 as compared to ages 31–45. Furthermore, the results indicate that the abilities for implementation of a solution (action program) and responding to rules and shifting (Rule Shift Card) significantly decrease between ages 46–60 (group 2) and the older group (76+) as well.

Besides the picture of decline in EF abilities with age, accurate screening of the mean scores and SD for each of the BADS tasks indicates that the deficits observed on the BADS’ tasks scores are not clearly gradual with aging (for example for the task of temporal judgment).

Hence, following those results, the implications of this decline in daily function should be further studied in relation to questions dealing with productivity and early retirement, as well as quality of life among people in this age range worldwide. In clinical work, an emphasis should be placed upon the individual’s profile change occurring in his EF control and its implications to his daily function (e.g., Cremer, Lozachmeur, & Pestieau, 2004).

The question of whether there was a decline in activities involving EF, such as handwriting production, was assessed by objective temporal and spatial measures using the ComPET. In the temporal domain, the results showed that performance time increased with age. These results are in line with those of previous studies (e.g., Dixon et al., 1993; Hackel, Wolfe, Bang, & Canfield, 1992; Rodriguez-Aranda, 2003).

The temporal domain was measured in the present study for both on-paper and in-air time per written stroke. In our previous studies with children and adults, we found that the in-air time measure reflects maturity and automatism in performance, as well as a decrease in performance caused by...
pathology (e.g., Gafni-Lachter & Rosenblum, 2009; Rosenblum et al., 2003a, 2003b; Werner et al., 2006). For example, studies showed that in air time per written stroke significantly decreased with age among children ages 8–14. However, this measure rose significantly in children with dysgraphia, (almost double) as compared to children with typical writing in the ages of 8–9 years (e.g., Gafni-Lachter and Rosenblum, 2009; Rosenblum et al., 2003a). When referring to adults, in air time significantly increased with age among participants in the ages of 60–94 years ($r = .58$, $p < .001$) (Rosenblum & Werner, 2005). Furthermore, among participants in similar age range (60–90), those with Mild Cognitive Impairments (MCI) and with mild AD spent a significantly longer time with the pen in the air (i.e., in-air time) than did healthy participants (Werner et al., 2006).

Following previous and current results, we can assume that an increase in the in-air time in writing may indicate a decrease in the fluency and effectiveness of handwriting performance that occurs with age. Furthermore, the in-air variable may not be just a measure of functional decline, but more specifically, may be an indication of difficulties in planning an activity in relation to space and time.

The Ratio measure strengthens the assumption that with increasing age, more time is required for planning the next phase in the hierarchical performance of handwriting in relation to the time of the actual performance on paper.

Significant differences were found between age groups not only for the temporal domain, but also for the spatial domain, as manifested in increased letter size with age. From a developmental point of view, it has been established that as a child grows, there is a decrease in letter size (Blote & Hamstra-Bletz, 1991; Gafni-Lachter & Rosenblum, 2009). This decrease is the result of more developed motor control in the distal areas of the hand and wrist, enabling the performance of hierarchical and sequential smaller movements (Thomassen & Teulings, 1985). On the other hand, age-related changes in manual function can cause deterioration in the control of finger pinch (finger pinch strength and steady precision finger pinch posture) (Ranganathan, Siemionow, Sahgal, Liu, & Yue, 2001), and these changes may lead to an increase in letter size, as found in the present study as well as in previous studies (Dixon et al., 1993; Rosenblum & Werner, 2005).

Given the results of decline with age in both EF and handwriting performance, the next step was to explore whether age predicts both EF control and handwriting performance.

The results of the regression analysis exhibited that, indeed, age accounted for 35% of the variance of EF control as reflected by the BADS profile score.

Prediction of the influence of age-related changes on real daily performance is not an easy task. Hence this process required a preliminary phase in order to discover which of the handwriting performance measures would best reflect changes occurring with age.

The results of the series of regressions enhance the uniqueness of in-air time as an objective measure that can be used to express changes occurring among the elderly, which are reflected in their real daily performance in handwriting. Results indicated that age accounted for 32% of the mean stroke in-air time, meaning that it reflects changes occurring in the individual performance abilities as a result of age-related decline.

As a rule, these findings reinforce the need for executive function assessment among adults in the context of everyday activities and show how age decline may be reflected through an everyday functioning ability, such as handwriting performance.

However, the results indicated that EF control as measured by the BADS test did not add further value to age, for the prediction of handwriting performance. Further studies with other standardized tools which focus on specific EF components as attention, working memory, organization, planning ahead etc with emphasis on the individual’s abilities are required in order to find the relationships between EF control and handwriting. The strength of the BADS tool as an ecological tool is also limited. The BADS is designated to evaluate a whole performance and hence the method of scoring (0–4) and its design are unable to answer the question of the exact changes in EF components resulting in age decline, and their relationships with daily performance as handwriting.

The findings of the current study should be regarded as preliminary and still need to be confirmed in future studies with larger cohorts of patients in regard to their validity, reliability, and sensitivity. However, taken together, the findings suggest that the BADS is indeed an ecologically valid assessment, which is sensitive to the decline in EF caused by aging. In addition to using the BADS, a
computer-based analysis of handwriting performance may be used as an objective, simple, quick, and relatively inexpensive method for evaluating the kinematics of handwriting movements. Combining both tools may present a picture of both individuals' EF decline as well as decline in their actual daily performances.

Such results have a particular importance in light of previous findings about the link that exists between executive function impairment and the individual's ability to participate fully in society found in varied pathologies related to aging, such as stroke (Baum et al., 2008), Alzheimer's disease (Hanks, Rapport, Millis, & Deshpande, 1999), Parkinson's disease (Klepac, Trkulja, Relja, & Babic, 2008) and psychiatric disorders (Gildengers et al., 2007; Baum et al., 2009). Further development of early screening for deficits in EF and performance ability among elderly people with and without any pathology may contribute to prevent decrease in their participation in society and hence advance their quality of life.

Furthermore, following the results of the relationships between age and both EF control and handwriting performance, future studies are needed to evaluate whether an intervention method focusing on accomplishment of varied tasks requires handwriting (e.g., crossword puzzles, writing the individual's life story etc.) may prevent such age connected deterioration in executive functions, which may influence daily function abilities (e.g., Ketcham & Stelmach, 2004; Yan & Zhou, 2009).

References


