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Some supplementary methods for the analysis of the D-KEFS

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Abstract

Supplementary methods for the analysis of the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) are made available including: (a) quantifying the number of abnormally low achievement scores exhibited by a case and accompanying this with an estimate of the percentage of the normative population expected to exhibit at least this number of low scores; (b) estimating the overall abnormality of a case's achievement score profile using the Mahalanobis Distance Index (MDI); (c) calculating a composite Executive Function Index score for a case and providing accompanying confidence limits; and (d) providing the percentile ranks for a case's achievement scores and Executive Index score (in the latter case confidence limits on scores are also expressed as percentile ranks). With the exception of the MDI, all the methods can be obtained using the formulas and tables provided in this paper. However, for the convenience of clinicians, and to reduce the possibility of clerical error, the methods have also been implemented in a computer program. More importantly the program allows the methods to be applied when only a subset of scores are available. The program can be downloaded (as a zip file) from the supplementary page on the journal's website or from www.abdn.ac.uk/~psy086/dept/DKEFS_Supplementary_Analysis.htm.

Keywords: Executive function; profile analysis; base rates; single-case methods

Introduction

Executive dysfunction in neurological, psychiatric, and learning disabled populations can be viewed as both a serious problem and as seriously problematic (Crawford & Henry, 2004). It is a serious problem because executive impairments typically have a much more profound impact on the capacity for independent living than other cognitive deficits (such as the more circumscribed problems that can arise from cortical posterior cortical lesions). It is seriously problematic because, quite aside from the difficulties in implementing successful interventions for such deficits, sound methods of assessing executive impairments have proved elusive (Crawford & Henry, 2004; Lezak, Howieson, Loring, Hannay, & Fischer, 2004).

The publication of the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001) is a positive development in the assessment of executive functioning. The D-KEFS gathers together an extensive range of some of the best available measures of executive functioning, offers a carefully standardized administration, and provides norms based on a large (N = 1750) stratified, census-matched, sample of the healthy population between the ages of 8 and 89 years. The aim of the present paper is to provide supplementary quantitative methods to assist in the interpretation of D-KEFS scores. The principal measures obtained from the D-KEFS are sixteen achievement scores (all achievement scores have a mean of 10 and standard deviation of 3); these will be the focus of the present paper.

Estimating the percentage of the normative population that will exhibit *j* or more abnormally low D-KEFS achievement scores

Information on the rarity or abnormality of test scores is fundamental in interpreting the results of a cognitive assessment (Crawford, 2004; Strauss, Sherman, & Spreen, 2006). When attention is limited to a single test (an achievement score in the present context), this information is immediately available; if an abnormally low score is defined as, say, one that falls below the 5^{th} percentile then, by definition, 5% of the normative population is expected to obtain a score that is lower (for example, in the case of achievement score, scores of 5 or lower are below the 5^{th} percentile).

However, if a full D-KEFS has been administered, there are sixteen achievement scores in total and the important question arises as to what percentage of the normative population would be expected to exhibit at least one abnormally low achievement score. This percentage will be higher than that for any single achievement score considered in isolation, and knowledge of it is liable to guard against over inference; that is, concluding impairment is present on the basis of one "abnormally" low score when such a result is not at all uncommon in the normative population. More generally, having observed the number of abnormally low scores exhibited by a case, it would be useful to know what percentage of the normative population would be expected to obtain at least as many abnormally low scores (Binder, Iverson, & Brooks, 2009; Brooks & Iverson, 2010; Crawford, Garthwaite, & Gault, 2007; Schretlen, Testa, Winicki, Pearlson, & Gordon, 2008) .

One approach to this issue would be to tabulate the percentages of the D-KEFS standardization sample exhibiting *j* or more abnormally low scores; that is, the question could be tackled empirically. However, as yet, this form of base rate data has not been provided for the D-KEFS. The alternative approach adopted here is to use a Monte Carlo method developed by Crawford, Garthwaite and Gault (2007) to estimate[1] the required quantities. This method has been used to estimate the

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[1] Note that the empirical approach also only provides an estimate because the quantity of interest is the percentage of the normative *population* that will exhibit a given number of abnormally low scores, rather than the percentage among those who

percentage of the normative population expected to exhibit *j* or more abnormally low index scores on the WAIS-III and WISC-IV (Crawford et al., 2007) and for short-form versions of both these scales (Crawford, Allum, & Kinion, 2008a; Crawford, Anderson, Rankin, & MacDonald, 2010); it has also been applied for similar purposes to other test batteries (Brooks & Iverson, 2010; Schretlen et al., 2008). These latter two studies compared the Monte Carlo estimates of base rates with base rates estimated using the empirical approach and found that the two methods exhibited a high degree of convergence.

An important advantage of the Monte Carlo approach over the empirical approach lies in its flexibility: it can be used to generate base rate when only a subset of the 16 achievement scores are available. Whether by choice or through necessity, it is common to administer only a subset of D–KEFS subtests. For example, a neuropsychologist may be under time pressure, or they may have a specific hypothesis they want to test which requires only particular subtests to be administered. Moreover, a patient may be easily fatigued, or may be suffering from physical or sensory disabilities that preclude administration of particular subtests. The authors' of the D-KEFS were fully aware of these practicalities. They note that "More than ever before, the clinician is often forced to adopt a flexible approach to test selection, tailoring the selected battery to fit each individual's presenting problem. The D-KEFS was designed to be used in a flexible manner. Each test …can be administered individually or with other D-KEFS tests" (p. 13).

The percentage of the normative population expected to exhibit a given number of abnormally low scores will vary markedly with the number of achievement scores involved. Moreover, even with a fixed number of achievement scores, the

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happened to make up the normative *sample.*

percentages will vary as a function of which particular subset of scores was selected (because the percentages are strongly determined by the magnitude of the correlations between scores, and these correlations vary). Thus an accurate estimate of these percentages requires that the base rate data are generated from the *particular* subset of achievement scores obtained for the case. It will be appreciated that it is completely impractical to use the empirical approach to make such data available as voluminous sets of tables would be required. A subset of the 16 achievement scores could consist of as few as two scores, or as many as 15; there are therefore 65,518 unique combinations.

In the present paper we use Crawford et al's (2007) method to produce base rate tables for the full set of 16 achievement scores. We also implement Crawford et al's method in a computer program that accompanies this paper. Because the program performs the required calculations in real time it is entirely flexible. That is, provision of base rate data is not limited to the case where the full set of 16 scores are available but rather can be calculated for any particular subset of achievement scores.

A global measure of the abnormality of an individual's achievement score profile

In neuropsychology much emphasis is placed on examining a case's profile of strengths and weaknesses (Crawford, 2004; Lezak et al., 2004; Strauss et al., 2006). To assist with this process the D-KEFS provides contrast scores; these contrast scores allow neuropsychologists to compare a patient's relative performance on different pairs of achievement scores. However, it would also be useful to have a single, multivariate, index of the *overall* abnormality of an individual's profile of achievement scores; that is, an index that quantifies how unusual a particular combination of achievement scores is.

One such index was proposed by Huba (1985) based on the Mahalanobis distance index (MDI). When the MDI is calculated for an individual's profile it yields a probability value. This value is an estimate of the proportion of the normative population that will exhibit a more unusual combination of scores. The method has been used to examine the overall abnormality of an individual's profile of subtest scores on the WAIS-R (Burgess, 1991; Crawford, 1994) and index score profiles for short-forms of the WAIS-III (Crawford et al., 2008a) and WISC-IV (Crawford et al., 2010).

In the present paper the Mahalanobis Distance Index is implemented for D-KEFS Achievement scores. It is not a practical proposition to calculate the MDI by hand, nor is it all practical to provide tabled values for it as there is a huge range of possible combinations of achievement scores. A patient's scores can range from 1 to 19 on each of the 16 achievement scores so that there are a myriad of potential profiles (moreover, as noted earlier, only a subset of achievement scores may have been obtained leading to an additional combinatorial explosion). Therefore the MDI for a case's profile of achievement scores is provided only by the computer program that accompanies this paper. Because, using the computer program, the MDI is calculated in real time this also means that (as was the case for base rate data for abnormally low scores) the method is entirely flexible. That is, provision of the MDI is not limited to the case where the full set of 16 scores are available but rather can be calculated for any particular subset of achievement scores.

Formation of a composite D-KEFS Executive Index

One of the strengths of the D-KEFS is that it provides a comprehensive assessment of executive functioning. However, this very comprehensiveness also poses some practical problems. Suppose for example that a neuropsychologist wishes to construct a profile of a case's relative strengths and weaknesses over a range of cognitive domains and, as part of this assessment, has administered a full D-KEFS. Suppose also that 15 measures of other cognitive domains have been obtained. (In practice there would often be many more measures than this; we will assume that the other measures are mainly composite scores such as WAIS-IV index scores, WMS-IV index scores etc). In this scenario there are 240 possible comparisons of D-KEFS achievement scores with the measures of other cognitive domains. It would clearly be a daunting task to try and assimilate this pattern of strengths and weakness when attempting to arrive at a formulation for the case.

In view of the foregoing it would sometimes be helpful to have available a composite Executive Index formed by combining the individual achievement scores (it would make sense to set the mean and standard deviation of this index to 100 and 15 respectively, as is done with other index scores used in neuropsychology). This would help ease the burden when attempting to compare a patient's D-KEFS performance with performance in other domains. In addition, the composite Executive Index should be more reliable than its individual components. This feature is important because, as has been pointed out elsewhere (Baron, 2004; Crawford, Sutherland, & Garthwaite, 2008b; Schmidt, 2003; Strauss et al., 2006), many of the individual D-KEFS achievement scores have modest reliabilities.

In the present paper we set out the methods for obtaining a D-KEFS Executive Index and of providing accompanying confidence limits on Executive Index scores. The statistics required to form this index and its accompanying confidence limits when all 16 achievement scores are available are provided. However, in keeping with the earlier emphasis on the need for flexibility, the accompanying computer program will also provide an Executive Index score (and accompanying limits) when only a subset of achievement scores is available.

Expressing D-KEFS scores and accompanying confidence limits as percentile ranks

The D-KEFS manual does not provide the percentile ranks corresponding to achievement scores, nor does the D–KEFS record form record such information. This may be a reflection of a general tendency within psychology to view percentile ranks as the poor relations of standardized scores (Bowman, 2002). However, as pointed out by Crawford and Garthwaite (2009), percentile ranks are the most directly meaningful way of expressing test performance. That is, an achievement score of, say, 6 is imbued with meaning only when we know that relatively few members (approximately 9%) of the normative population are expected to obtain lower scores; that is, when we know the score is at the 9th percentile.

Experienced psychologists are liable to have developed an internalized lookup table mapping the various standardized scores (i.e., subtest scores, Index scores etc) on to their corresponding percentile ranks so that it might be argued that provision of a score's percentile rank is unnecessary. However, not all psychologists are experienced and, even when they are, their internalized lookup tables may still be relatively sparsely populated, being limited to various landmark scores (e.g., scores corresponding to the 10th and 5th percentile etc). It thus makes sense to directly accompany scores with their percentile ranks so that information on the rarity or otherwise of such scores is immediately available (Crawford & Garthwaite, 2009). In keeping with these arguments the present paper provides the means to express both achievement scores and Executive Index scores as percentile ranks.

Crawford and Garthwaite (2009) also proposed that confidence limits on test scores should be expressed as percentile ranks. All authorities on psychological measurement agree that confidence limits should accompany test scores. However, it remains the case that some neuropsychologists do not routinely record confidence intervals. There is also the danger that others will dutifully record such intervals but that, thereafter, these intervals play no further part in test interpretation. Thus it could be argued that anything that serves to increase the perceived relevance of confidence limits should be encouraged. Crawford and Garthwaite (2009) suggest that expressing confidence limits as percentile ranks is one way to help achieve this as they are more tangible than standard score intervals. For this reason confidence limits on Executive Index scores are expressed on an index score metric *and* as percentile ranks.

Method

This research was approved by the School of Psychology Ethics Committee, University of Aberdeen, and was conducted in accordance with the Helsinki Declaration.

D-KEFS standardization sample age bands

The methods developed in the present paper require either the reliabilities of the D-KEFS achievements scores, their intercorrelations, or both. The D-KEFS technical manual provides such data for three principal normative age bands: 8-19, 20-49, and 50-89 years of age. For example, the correlations between achievement scores for these age bands are presented in Tables 3.1 to 3.15 of the manual. In the present paper all the quantitative methods are applied separately for each of these three normative age bands.

Estimating the percentage of the normative population that will exhibit *j* or more abnormally low D-KEFS achievement scores

As noted, Crawford et al's (2007) Monte Carlo method was used to generate base rate data on the number of abnormally low achievement scores. Full technical details of this method are provided in the aforementioned paper and thus are not repeated here. In essence the method simulates observations (one million) from the normative population (to do this it requires only the correlation matrix of scores and their standard deviations). For each simulated member of the normative population it records the number of scores classified as abnormally low according to a specified criterion (e.g., below the 5th percentile) and reports the estimated percentage of the normative population that will exhibit *j* or more abnormally low scores.

In the present study the Monte Carlo simulation was run by drawing observations from a multivariate normal distribution in which each of the marginal distributions had a mean of 10 and standard deviation of 3. Observations drawn from this distribution were then rounded to integers thereby simulating a vector of integer-valued achievement scores. For each vector of observations (i.e., for each simulated member of the normative population) the number of scores meeting the specified criterion for an abnormally low score was recorded and used to determine what percentage of the normative population would be expected to exhibit *j* or more abnormally low scores.

Neuropsychologists are liable to differ in their preferred definition of an abnormally low score. Therefore the base rate data were generated for a range of criteria for abnormality, ranging from the liberal criterion of a score of 7 or less (i.e., one standard deviation below the mean; percentile rank = 15.8) through to the stringent criterion of a score of 3 or less (i.e., 2.333 standard deviations below the mean; percentile rank = 0.98).

Calculating the Mahalanobis Distance Index (MDI) for D-KEFS achievement score profiles

The formula for Huba's (1985) Mahalanobis distance index (MDI) of the abnormality of a case's profile of scores on *k* tests is

$$\left(\mathbf{x}-\overline{\mathbf{x}}\right)' \mathbf{W}^{-1}\left(\mathbf{x}-\overline{\mathbf{x}}\right), \tag{1}$$

where $\mathbf{x}$ is the vector of scores for the case on each of the *k* tests of a battery, $\overline{\mathbf{x}}$ is the vector of means for the controls, and $\mathbf{W}^{-1}$ is the inverse of the covariance matrix for the battery's standardization sample (the covariance matrix is easily obtained from the D-KEFS correlation matrix for each of the three age bands by multiplying each element by 9). When the MDI is calculated for an individual's achievement score profile it is evaluated against a chi-square distribution on *k* degrees-of-freedom (*k* would be 16 if a full D-KEFS had been administered but will vary between 2 and 16 depending on which scores a case has available). The probability obtained is an estimate of the proportion of the normative population that would exhibit a more unusual combination of achievement scores. A case example of the use of the MDI is provided in a later section.

Formation of the D-KEFS Executive Index

To form a composite Executive Index the available achievement scores for a case are simply summed and entered into the following formula to convert this sum to an Index score having a mean of 100 and standard deviation of 15.

$$\text{Executive Index score} = \frac{15}{s_{\text{sum}}}\left(X_{\text{sum}} - \overline{X}_{\text{sum}}\right) + 100, \qquad (2)$$

where X_{sum} = the sum of a case's achievement score, s_{sum} = the population standard deviation of the sum of the achievement scores, and $\overline{X}_{\text{sum}}$ = the population mean of the sum of the achievement scores (Crawford, 2004).

It can be seen that the formula requires the standard deviation of the sum of the achievement scores. This can be obtained by summing the elements of the D-KEFS covariance matrix (to obtain the variance of the composite) and taking its square root (to obtain the required standard deviation of the composite). Thus for example, for the 8 to 19 year old age group of the standardization sample, the sum of the covariance matrix is 588.984 and thus the standard deviation is 24.269. The standard deviations of the sum of the 16 achievement scores for each of the three standardization sample age groups are presented in Table 4.

To illustrate, if all 16 achievement scores are available for a case, then the population mean for this sum is 160 (each individual achievement scores has a mean of 10) and, as noted, its standard deviation is 24.269. If the sum of the case's achievement scores was 112 then, entering these figures into formula 2, the case's Executive Index score is 70 (they are two standard deviations below the mean).

A psychologist need never carry out these calculations as the computer program accompanying this paper provides a case's Executive Index score. Moreover, as the calculations (including obtaining the standard deviation of the sum of achievement scores) are carried out in real time, an Executive Index score can be calculated even if only a subset of achievement scores is available.

In passing, note that the foregoing example provides a particularly clear illustration of the fact that an individual's composite score will always be more extreme than the simple "average" of their standing on the components of the composite and this difference will become more marked as the number of components increases (the exception would occur when the components are perfectly correlated; not the case here, nor indeed the case for any composite cognitive ability score). For example, a sum of 112 could be obtained if the individual obtained a score of 7 on each achievement score. Thus, although each achievement score is exactly one standard deviation below the mean, the composite score is two standard deviations below the mean (a score that is one standard deviation below the mean on any one test is not indicative of low ability; however obtaining a score that is one standard deviation below the mean on *all* tests represents particularly poor performance). In our experience a failure to appreciate that this is a universal feature of composite scores is a common source of confusion among psychologists, hence the brief digression.

Reliability and standard errors of measurement for the D-KEFS Executive Index

The reliability of the D-KEFS Executive Index was calculated using the standard formula for the reliability of a composite (Mosier, 1943); see Crawford (2008a) for a more readily accessible treatment. This formula requires the standard deviations of the components (achievement scores have a common standard deviation of 3), the reliabilities of the components, and the matrix of correlations between the components.

Ideally, the reliabilities of the components should be obtained from the same test session (i.e., internal consistency coefficients should be used). However, as the authors of the D-KEFS point out, the nature of many of the subtests preclude calculation of these coefficients (Delis et al., 2001) and so they used the test-retest method to estimate reliability. Therefore, the reliabilities of the achievement scores were obtained from the test-retest reliability coefficients for each of the three age groups, as reported in the D-KEFS technical manual (note that internal consistency information is presented for a few of the subtests).

The technical manual does not record any reliability information for one of the two Tower Test achievement scores (Move Accuracy Ratio). Therefore, the reliability of the other Tower Test achievement score (Total Achievement Score) was used as an estimate of the reliability of the former score. Note that it would often be the case that a ratio score would be less reliable than a simple score, thereby suggesting that the solution above is questionable. However, this is not the case here as one of the two quantities used in its formation is error free (the minimum number of moves required for successful completion).

In the case of the D-KEFS Color-Word Interference test, one of the contrast scores compares Inhibition/Switching with combined Naming + Reading. Test-retest reliability data are not presented for combined Naming + Reading. However, internal consistency coefficients are presented and so the reliability was estimated using the averaged internal consistency coefficients within each of the three age groups.

Expressing scores and confidence limits on scores as percentile ranks

Expressing an achievement score or Executive Index score in the form of a percentile rank is easily achieved: the score is converted to a z score and the probability for this quantile (obtained form a table of areas under the normal curve or algorithmic equivalent) is multiplied by 100. Thus the percentile rank for an achievement score of 7 ($z = -1.0$) is 15.9 (or 16 if rounded to an integer). Exactly the same procedure is used to express confidence limits as percentile ranks: for example, if the lower 95%

confidence limit for an Executive Index score is 70 ($z = -2.0$), then the percentile rank for this lower limit is 2.3.

Results and Discussion

Estimated percentages of the normative population that will exhibit *j* or more abnormally low D-KEFS achievement scores

The results of applying Crawford et al's. Monte Carlo method to estimate the percentage of the normative population exhibiting *j* or more abnormally low scores are presented in Tables 1 to 3 for the three normative age bands. Taking Table 2 (20-49 years of age) for illustrative purposes, it can be seen that, if an abnormally low score is defined as a score of 5 or less, then almost half of the normative population (49.36%) are expected to exhibit at least one such abnormally low score. Using the same criterion for abnormality, a substantial percentage is also expected to exhibit two or more such scores (25.60%). Thereafter the percentages fall with increasing rapidity; for example, only 2.51% are expected to exhibit six or more abnormally low scores. This criterion (a score of 5 or less) is our own preferred criterion for an abnormally low score (hence the percentages for this criterion appear in bold in the tables and is also the default option in the accompanying computer program). It can be seen that the percentages vary markedly with the choice of criterion. For example, if the most liberal of the criteria is applied (a score of 7 or less) then a very substantial majority of the normative population (84.98%) are expected to exhibit at least one abnormally score.

As discussed, the percentage of the normative expected to exhibit *j* or more abnormally low scores will also vary markedly with the number of scores available (to a lesser extent it will also vary as a function of which particular combination of scores are available). Therefore, if a case has only been administered a subset of achievement scores, the computer program accompanying this paper should be used to obtain the relevant base rate data. The program also does away with the need to count the number of abnormally low scores exhibited by a case as it applies the user's chosen criterion for abnormality and performs the count.

For purposes of illustration, suppose that only the first seven D-KEFS achievement scores had been obtained (the Sorting Test Free Sorting Confirmed Sorts through to the Twenty Questions Total Weighted Achievement Score). Suppose also that an abnormally low score has been defined as a score of 5 or less, and that two of the case's scores meet this criterion. It is estimated that 11.77% of the normative population will exhibit this number of abnormally low scores; this compares to 25.60% if all 16 scores had been obtained.

Issues associated with the interpretation of base rates when there are multiple tests

The estimated percentage of the population exhibiting at least as many low scores as a case can serve as a useful xxx against over inference. However, it is important to appreciate that such data cannot be viewed in isolation; rather it needs to be integrated with other information in arriving at a formulation. Thus, for example, as pointed out by a reviewer, if a case's low scores were all on measures that tap a common construct such as working memory this would be more clinically significant and would be given more weight than a profile in which the same number of low scores was obtained across measures with less in common. Furthermore, the pattern of low achievement scores should be interpreted in the light of potential converging evidence from other sources such as neuroimaging or behavioural observations (e.g., consistently low scores on tasks with a working memory component combined with evidence of structural abnormality in dorsolateral pre-frontal cortex would constitute convincing evidence of an acquired impairment even if a sizeable percentage of the normative population would exhibit the same overall number of low scores as the case).

A further issue to be considered is that, on the basis of results found for other test batteries, the base rates for low scores on the D-KEFS are liable to vary as a function of a case's values on various attribute variables, such as years of education. For example, Brooks, Holdnack and Iverson (in press) have shown that the number of low scores on the WAIS-IV and WMS-IV varies with level of education and estimated premorbid ability. Recent work on allowing for covariates in the analysis of individual's test scores (Crawford, Garthwaite, & Ryan, in press) holds out the prospect that the Monte Carlo methods used in the present study could be extended to provide conditional base rate information. However, as things stand, it would not be possible to apply these methods to the D-KEFS as they would require the correlations between D-KEFS achievement scores and the variables used to condition the scores (e.g., years of education); such correlations are not reported in the D-KEFS technical manual.

Thus, in summarizing this latter issue, the present Monte Carlo method does exactly what it claims to do: it estimates the percentage of the *overall* normative population expected to exhibit a given number of low scores. The number of low scores may (and probably will) vary as a function of a number of attribute variables so that it would be useful if the information provided here could be supplemented in the future with base rates for various sub-populations (e.g., those with low, medium, or high years of education). This could potentially be achieved by statistical means if the correlations between the scores and attribute variables were made available, or could be obtained using empirical methods (i.e., by stratifying the standardization sample into bands based on values of a particular attribute variable and tabulating the number of participants exhibiting low scores separately for each of these bands).

Finally, as pointed out by a reviewer, the present method of obtaining base rates for low scores on the D-KEFS only allows for the multiple tests within the D-KEFS itself. In practice, additional tests from other batteries will have been administered so that it would be useful to be able to quantify the percentages exhibiting a given number of low scores over *all* tests administered in a given assessment. Obtaining these base rates would require that all measures were co-normed as the Monte Carlo method requires the correlations between measures. Co-norming would also be required to use the empirical method to quantify the base rates (as the data could only be tabulated if normative cases had been administered all the tests concerned).

Indeed the Monte Carlo method is a more practical proposition for tackling this type of problem as (a) it could generate estimates based on correlational data obtained from a smaller sample that had been administered a set of tests (rather than requiring a full normative sample), and (b) it would be more flexible in that it could easily allow for the fact that a particular case had only been administered a subset of the full array of measures.

The Mahalanobis Distance Index (MDI) for D-KEFS achievement score profiles

The application of the MDI is best illustrated with an example. Suppose that 14 of the 16 achievement scores were obtained from a case aged 45 years (let us suppose that the two color word achievement scores had been omitted) and that the scores obtained (presented in the standard order for achievement scores used in the manual and record form) were: 6, 9, 8, 7, -, -, 8, 12, 12, 8, 8, 9, 12, 12, 13, and 12. The chi square value for this profile of scores is 28.834 (on 14 df) and is statistically significant, *p* = 0.0110. Therefore we can reject the null hypothesis that this profile is an observation from the profiles in the normative population (i.e., it is unusual). Multiplying this probability by 100 also provides us with the estimated percentage of the normative population that would exhibit an even more unusual profile than the case (1.10%). It can be seen then that the probability value serves both as a significance test and a point estimate of the abnormality of the abnormality of the profile (Crawford et al., 2008a).

The D-KEFS Executive Index: Reliabilities and standard errors of measurement

The reliabilities of the Executive Index based on all 16 achievement scores for each of the three standardization sample age bands are presented in Table 4. It can be seen that the Index has high reliability (ranging from 0.90 to 0.92 across the three age bands). These reliabilities are much higher than those of the vast majority of the individual achievement scores that contribute to the Index.

The standard errors of measurement in Table 4 can be used to set confidence intervals on D-KEFS contrast scores. Experts on psychological measurement are unanimous in recommending that test scores should be accompanied by confidence intervals. These intervals serve the general purpose of reminding us that scores are fallible (i.e., they avoid reifying the observed score) and serve the specific and practical purpose of quantifying the effects of such fallibility (Crawford & Garthwaite, 2009). Two-sided 95% confidence intervals are formed by multiplying the relevant SEM by 1.96 and then adding and subtracting this quantity from the obtained Index score.

A worked example of the formation of a case's Executive Index score was provided in the Method section: the sum of the case's 16 achievement scores was 112 and this converted to an Executive Index score of 70 (Percentile Rank = 2.4; note the percentile rank is calculated before rounding the Index score hence the minor difference between the percentile rank of 2.3 for a score that was exactly 2 SDs below the mean). The standard error of measurement for the Executive Index in the 8-19 age band is 4.753 (see Table 4) and this gives a 95% confidence interval for the case's score of 61 to 80. Expressing this interval in the form of percentile ranks, the limits are from the 0.5^{th} percentile to the 8.7^{th} percentile.

The standard errors of measurement recorded in Table 4 are primarily used to set confidence limits on scores. However they can also be used to test for a reliable difference between the Executive Index and Index scores on other instruments (e.g., the WAIS-IV, WISC-IV, or WMS-IV etc), provided that the standard error of measurement for the other Index is also known. Armed with the two standard errors, the standard error of measurement of the difference ($\mathrm{SEM_D}$) can be calculated from the formula

$$\mathrm{SEM_D} = \sqrt{\mathrm{SEM_{EI}^2} + \mathrm{SEM_{OI}^2}}\,, \tag{3}$$

where $\mathrm{SEM_{EI}}$ is the standard error for the Executive Index and $\mathrm{SEM_{OI}}$ is the standard error for the other Index of interest. Dividing the difference between a case's scores on the two indexes by the $\mathrm{SEM_D}$ yields a *z* score that can then be tested for significance; see Crawford, Anderson, Rankin, and MacDonald (2010) for a fuller treatment. The computer program that accompanies this paper calculates and reports the standard error of measurement for the Executive Index based only on the achievement scores available for a particular case. Therefore comparisons such as those outlined above can still be conducted when a full D-KEFS has not been administered.

Use of the supplementary methods

Although we consider that all of the methods developed here are useful, they are not interdependent. Thus it is perfectly possible for a psychologist to pick and choose among them. That is, a particular psychologist may find the ability to generate base rate data on the number of abnormally low scores particularly useful but have reservations over the use of the composite Executive Index whereas another may take the diametrically opposite view. Still others may find that expressing confidence limits on a case’s score as percentile ranks helps them assimilate the degree of uncertainty attached to a case’s score whereas others consider they already have a sufficient grasp of the uncertainties without requiring such additional support.

Although the methods are not interdependent it is worth noting that they can be used in a complimentary fashion. For example, the estimate of the percentage of the normative population that will exhibit at least as many low scores as a case will potentially identify consistently poor performance. In contrast, the MDI is relatively insensitive to the *absolute* level of performance on each of the achievement scores but is sensitive to the overall *profile* of performance. These contrasting features are best illustrated with a concrete example. Suppose that a case (aged between 20 and 49) has been administered all sixteen achievement scores and obtains a score of 7 on all of these. This is a very poor level of performance: from Table 2 it is estimated that less than 0.01% of the normative population will obtain scores of 7 or less on all 16 achievement scores (the table entry is recorded as 0.00% as it only reports percentages to two decimal places – the computer program reports the figures to three decimal places and provides an estimate of 0.003%). Although poor, the case’s performance is remarkably consistent. For this example the chi square for the MDI is not significant (χ^2 =5.033 on 16 df, p = 0.996) underlining that the MDI is not sensitive to a case's absolute levels of performance.

In contrast, suppose that everything was the same as in the first example but that, on every odd numbered achievement score, the case obtained a score of 13 (that is, the case's scores were 13, 7, 13, 7, …,13, 7 etc). In this scenario the MDI is highly significant: χ^2 = 116.05, p <0.00001. The *profile* of scores is therefore *highly* unusual; for all intents and purposes nobody in the normative population would be expected to exhibit a more unusual profile of scores. In this latter scenario eight of the case's scores are $\leq$ 7; it is estimated that 9.3% of the normative population will exhibit this number of low scores (see Table 2). It can be seen then that the base rate data on low scores and the MDI are complimentary in the process of identifying cognitive difficulties. Needless to say if both methods converge to suggest either abnormal or normal performance then interpretation of the results is simplified and the clinician can have more confidence when arriving at a formulation.

The MDI may also play a useful role in determining how much weight should be afforded to the Executive Index. If the MDI suggests that combination of achievement scores is highly unusual (i.e., there are sizeable discrepancies within the profile) then the Executive Index is clearly less useful as a summary of a case's executive abilities.

Finally, the MDI may also be useful in helping psychologists decide how much weight to place on the D-KEFS contrast scores. As previously noted, contrast scores quantify the discrepancies in performance between pairs of achievement scores. However, as there are 14 contrast scores, the same issue arises as when the concern was with scores that were abnormally low: an individual contrast score (i.e., an individual pairwise comparison) may suggest an abnormal discrepancy but it may be very common for members of the normative population to show at least one such discrepancy out of the total of 14 contrasts. Thus, if the MDI suggests that a case's profile of performance is not at all unusual (that is, a sizeable percentage of the normative population are expected to obtain a more unusual profile of performance) then this single contrast score, unless supported by other sources of information, should not be given much weight in arriving at a formulation of a case's cognitive status. In contrast, if the MDI suggests that the overall profile is unusual, then the contrast score results and the MDI results converge to suggest an abnormal pattern of performance.

Computer program for supplementary analysis of D-KEFS achievement scores

As referred to above, a compiled (i.e., ready-to-run) computer program for PCs, DKES_Supplementary_Analysis_EXE, accompanies this paper. With the exception of the Mahalanobis distance index, all the methods presented here can be applied either using the tables provided or by simple calculations on the part of the user. However, the program provides a very convenient alternative for busy psychologists as, on being provided with a case's achievement scores, it performs all of the necessary calculations and records the results. The computer program has the additional advantage that it will markedly reduce the likelihood of clerical error. Research shows that psychologists make many more simple clerical errors than we like to imagine (e.g., see Faust, 1998; Sherrets, Gard, & Langner, 1979; Sullivan, 2000).

To use the program the user need only select the normative age band for their case, and select their preferred criterion for a low score (i.e., a score of ≤ 7, or ≤ 5, etc); this is done using radio buttons. Thereafter the case's achievement scores can be entered. If, as will be common in practice, only a subset of achievement scores have been administered the data field for the omitted subtests need simply be left blank. There is also the option of adding user's notes (e.g., a Case ID, date of testing etc.) for future reference. An illustrative example can be seen in Fig 1a which presents a screen capture of the input form for the program. In this example it can be seen that the case falls in the 20 to 49 age band (as indicated by the checked radio button), and that an achievement score of 5 or less has been selected as the criterion for an abnormally low score. It can also be seen that not all achievement scores have been administered, hence some data fields have been left blank (there are 16 achievement scores in total, the scores are entered by tabbing /scrolling through the data fields; in the present case achievement scores 11 to 16 are displayed).

The output of the program reproduces the case's scores and accompanies them with their percentile ranks. The number of a case's scores that meet the user's criterion for a low score is recorded along with the percentage of the normative population expected to exhibit at least this number of low scores. This is followed by the results of applying the Mahalanobis Distance Index to the case's score profile.

Next the cases Executive Index score is reported on the standardized metric (i.e., mean = 100, SD =15) and as a percentile rank; these are accompanied by their corresponding confidence limits. Finally, the composite reliability of the Executive Index is reported along with its standard error of measurement (as noted, these statistics will vary as a function of both the number of achievement scores available and the reliability of the particular achievement scores and are therefore calculated in real time). As referred to earlier, the standard error of measurement can be used to test for reliable differences between a case's Executive Index score and scores on other tests (provided of course that the standard error of measurement for the other tests are available – for most standardized tests they would be). The results from the program can be viewed on screen, saved to a file, or printed. Because the program performs a Monte Carlo simulation to obtain the base rates for low scores there will typically be a delay of around 20 seconds before the results are available.

Fig. 1b provides an illustrative example of the results form based on the input data entered in Fig 1a; the full set of results for the case cannot be viewed simultaneously hence the screen capture shows only the last few achievement scores (the case's scores plus their accompanying percentile ranks) but does include all other results. The program can be downloaded, either as an executable file or as a zip file, from the following web page: www.abdn.ac.uk/~psy086/dept/DKEFS_Supplementary_Analysis.htm. Alternatively, the zip file version of the program can be downloaded from the supplementary page for this paper on the journal's web site.

Conclusion

The D-KEFS is a complex and multifaceted instrument. That is as it should be, given that the D-KEFS aims to assess a staggeringly complex and multifaceted system. However, the very complexity of the D-KEFS and (ironically perhaps) its flexibility does present significant challenges for test users. The aim of the present paper was to develop a package of quantitative methods to assist with test interpretation. Although some of the underlying calculations required to implement these methods are complex, this is not an impediment to their adoption as the tabled values and, particularly, the accompanying computer program, makes this process both quick and reliable.

The provision of quantitative methods of analysis by no means undermines the role of the psychologist in decision making. The psychologist still needs to employ the uniquely human ability of combining quantitative results with the qualitative data obtained from interview and testing in order to arrive at a satisfactory formulation of a case's cognitive strengths and weaknesses and thereafter develop its implications for management and/or intervention. Thus, although the focus of the present paper is firmly quantitative, it should not be taken as a plea for an actuarial / mechanistic approach to assessment.

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Table 1. Percentage of the normative population **aged 8 to 19 years** expected to exhibit at least *j* abnormally low D-KEFS achievement scores; increasingly stringent criteria for an abnormally low score are applied ranging from a score of 7 or less (Percentile Rank= 15.9) to a score of 3 or less (PR = 0.98).

	Estimated percentage of normative population exhibiting *j* or more abnormally low D-KEFS achievement scores															
Criterion	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
≤7 (PR=15.9)	86.87	68.95	52.46	38.56	27.45	18.93	12.54	7.99	4.84	2.76	1.45	0.70	0.29	0.09	0.02	0.00
≤6 (PR=9.12)	71.55	46.88	30.14	19.02	11.70	6.98	4.03	2.22	1.17	0.58	0.26	0.11	0.04	0.01	0.00	0.00
≤5 (PR=4.78)	**51.64**	**26.46**	**13.94**	**7.36**	**3.81**	**1.95**	**0.97**	**0.47**	**0.22**	**0.09**	**0.04**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**
≤4 (PR=2.27)	32.12	12.31	5.16	2.22	0.97	0.42	0.18	0.08	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
≤3 (PR= 0.98)	17.14	4.76	1.55	0.54	0.19	0.07	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note. The above figures assume that all 16 achievement scores were obtained; when only a subset of scores is available for a case the computer program accompanying this paper records the percentage of the population expected to exhibit at least as many abnormally low scores as the case

Table 2. Percentage of the normative population **aged 20 to 49 years** expected to exhibit at least *j* abnormally low D-KEFS achievement scores; increasingly stringent criteria for an abnormally low score are applied ranging from a score of 7 or less (Percentile Rank= 15.9) to a score of 3 or less (PR = 0.98).

	Estimated percentage of normative population exhibiting *j* or more abnormally low D-KEFS achievement scores															
Criterion	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
≤7 (PR=15.9)	84.98	66.25	50.48	37.75	27.67	19.82	13.81	9.30	6.02	3.71	2.14	1.21	0.52	0.19	0.05	0.00
≤6 (PR=9.12)	69.09	44.83	29.52	19.38	12.52	7.95	4.94	2.97	1.72	0.95	0.48	0.22	0.08	0.03	0.00	0.00
≤5 (PR=4.78)	**49.36**	**25.60**	**14.15**	**8.00**	**4.51**	**2.51**	**1.37**	**0.73**	**0.37**	**0.18**	**0.08**	**0.03**	**0.01**	**0.00**	**0.00**	**0.00**
≤4 (PR=2.27)	30.56	12.24	5.56	2.62	1.29	0.63	0.30	0.14	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.00
≤3 (PR= 0.98)	16.34	4.91	1.80	0.71	0.29	0.12	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note. The above figures assume that all 16 achievement scores were obtained; when only a subset of scores is available for a case the computer program accompanying this paper records the percentage of the population expected to exhibit at least as many abnormally low scores as the case

Table 3. Percentage of the normative population **aged 50 to 89 years** expected to exhibit at least *j* abnormally low D-KEFS achievement scores; increasingly stringent criteria for an abnormally low score are applied ranging from a score of 7 or less (Percentile Rank= 15.9) to a score of 3 or less (PR = 0.98).

	Estimated percentage of normative population exhibiting *j* or more abnormally low D-KEFS achievement scores															
Criterion	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
≤7 (PR=15.9)	84.90	64.67	49.05	36.85	27.41	20.09	14.46	10.07	6.78	4.36	2.64	1.45	0.69	0.27	0.07	0.00
≤6 (PR=9.12)	68.52	43.35	28.65	19.18	12.83	8.52	5.54	3.49	2.12	1.24	0.67	0.32	0.13	0.04	0.01	0.00
≤5 (PR=4.78)	**48.51**	**24.70**	**14.00**	**8.23**	**4.91**	**2.91**	**1.70**	**0.98**	**0.53**	**0.27**	**0.13**	**0.06**	**0.02**	**0.00**	**0.00**	**0.00**
≤4 (PR=2.27)	29.85	11.90	5.67	2.89	1.52	0.81	0.42	0.22	0.10	0.05	0.02	0.01	0.00	0.00	0.00	0.00
≤3 (PR= 0.98)	15.95	4.86	1.92	0.85	0.39	0.18	0.08	0.04	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Note. The above figures assume that all 16 achievement scores were obtained; when only a subset of scores is available for a case the computer program accompanying this paper records the percentage of the population expected to exhibit at least as many abnormally low scores as the case

Table 4. Reliabilities and standard errors of measurement (SEM) for the D-KEFS Executive Index for three age groups

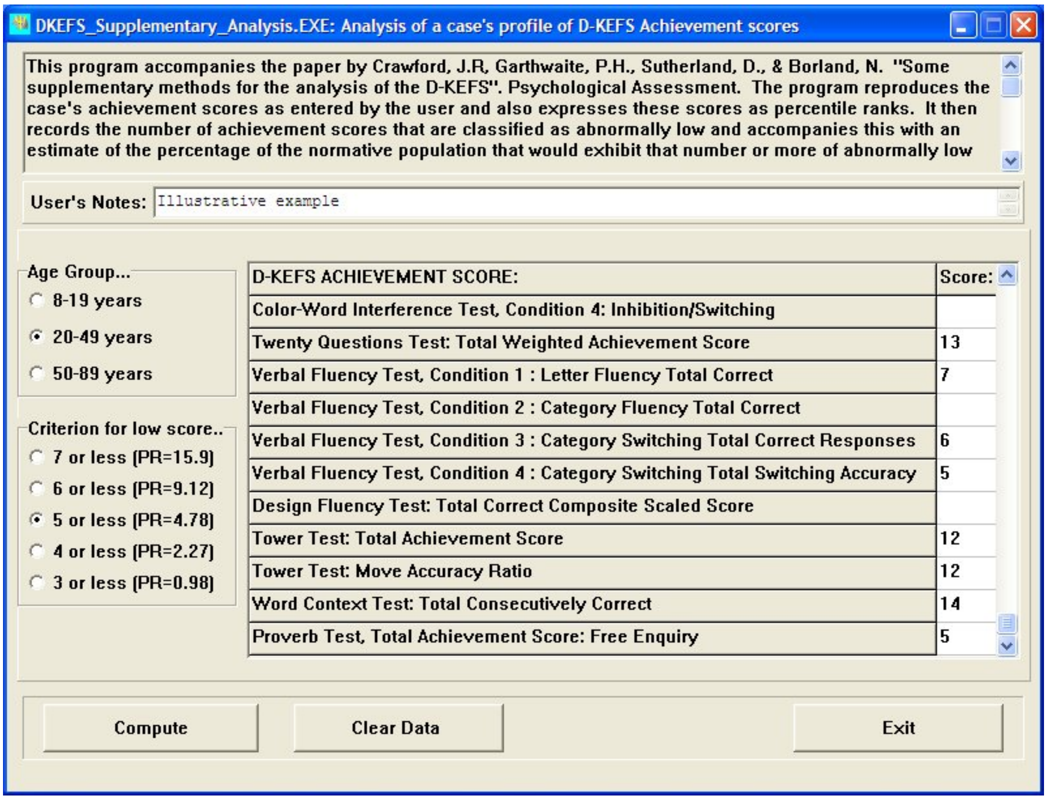
Age group	SD of sum	Reliability	SEM
8-19 years	26.739	0.92	4.23
20-49 years	24.269	0.90	4.75
50-89 years	25.981	0.90	4.72

Note. The above figures assume all 16 achievement scores were administered; when only a subset of the scores are available the computer program accompanying this paper calculates (and reports) the equivalent figures in real time

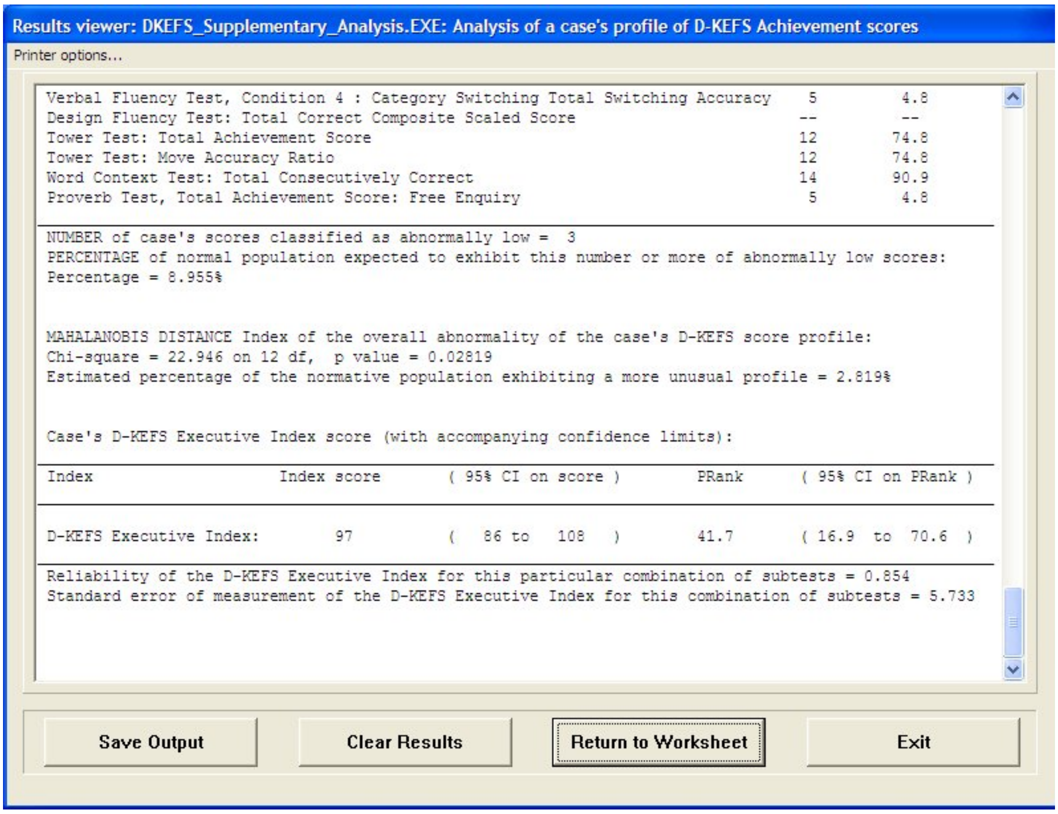
Figure legend

Fig. 1. Screen captures of the input form (1a) and results form (1b) for the accompanying computer program

1a


DKEFS_Supplementary_Analysis.EXE: Analysis of a case's profile of D-KEFS Achievement scores
This program accompanies the paper by Crawford, J.R, Garthwaite, P.H., Sutherland, D., & Borland, N. "Some supplementary methods for the analysis of the D-KEFS". Psychological Assessment. The program reproduces the case's achievement scores as entered by the user and also expresses these scores as percentile ranks. It then records the number of achievement scores that are classified as abnormally low and accompanies this with an estimate of the percentage of the normative population that would exhibit that number or more of abnormally low
User's Notes: Illustrative example
Age Group...
8-19 years
20-49 years
50-89 years
Criterion for low score..
7 or less (PR=15.9)
6 or less (PR=9.12)
5 or less (PR=4.78)
4 or less (PR=2.27)
3 or less (PR=0.98)
D-KEFS ACHIEVEMENT SCORE: | Score:
Color-Word Interference Test, Condition 4: Inhibition/Switching
Twenty Questions Test: Total Weighted Achievement Score | 13
Verbal Fluency Test, Condition 1 : Letter Fluency Total Correct | 7
Verbal Fluency Test, Condition 2 : Category Fluency Total Correct
Verbal Fluency Test, Condition 3 : Category Switching Total Correct Responses | 6
Verbal Fluency Test, Condition 4 : Category Switching Total Switching Accuracy | 5
Design Fluency Test: Total Correct Composite Scaled Score
Tower Test: Total Achievement Score | 12
Tower Test: Move Accuracy Ratio | 12
Word Context Test: Total Consecutively Correct | 14
Proverb Test, Total Achievement Score: Free Enquiry | 5
Compute
Clear Data
Exit

1b


Results viewer: DKEFS_Supplementary_Analysis.EXE: Analysis of a case's profile of D-KEFS Achievement scores
Printer options...
Verbal Fluency Test, Condition 4 : Category Switching Total Switching Accuracy 5 4.8
Design Fluency Test: Total Correct Composite Scaled Score -- --
Tower Test: Total Achievement Score 12 74.8
Tower Test: Move Accuracy Ratio 12 74.8
Word Context Test: Total Consecutively Correct 14 90.9
Proverb Test, Total Achievement Score: Free Enquiry 5 4.8
NUMBER of case's scores classified as abnormally low = 3
PERCENTAGE of normal population expected to exhibit this number or more of abnormally low scores:
Percentage = 8.955%
MAHALANOBIS DISTANCE Index of the overall abnormality of the case's D-KEFS score profile:
Chi-square = 22.946 on 12 df, p value = 0.02819
Estimated percentage of the normative population exhibiting a more unusual profile = 2.819%
Case's D-KEFS Executive Index score (with accompanying confidence limits):
Index Index score (95% CI on score) PRank (95% CI on PRank)
D-KEFS Executive Index: 97 (86 to 108) 41.7 (16.9 to 70.6)
Reliability of the D-KEFS Executive Index for this particular combination of subtests = 0.854
Standard error of measurement of the D-KEFS Executive Index for this combination of subtests = 5.733
Save Output
Clear Results
Return to Worksheet
Exit