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Permutation tests in the educational and behavioral sciences: A systematic review

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Permutation tests in the educational and behavioral sciences: A systematic review

In many educational and behavioral studies, the assumptions of common parametric hypothesis tests (e.g., random samples from defined populations, sampled populations are normally distributed, and of equal variance) are considered implausible (e.g., Adams & Anthony, 1996; Edgington & Onghena, 2007; Hunter & May, 2003; Ludbrook, 1994; Manly, 1997). An alternative to using parametric tests is to use nonparametric rank tests (e.g., Wilcoxon-Mann-Whitney tests and Wilcoxon signed test). These tests transform the original data into ranks and obtain the probability distribution for a given test statistic under the null hypothesis (Lehmann & D'Abrera, 2006). However, nonparametric rank methods are not unproblematic either. A common criticism is that the use of nonparametric methods results in a loss of information when reducing the data to ranks, eventually resulting in a reduction of the statistical power and efficiency (Edgington & Onghena, 2007).

Because of the problems associated with parametric and standard nonparametric tests, permutation tests (PTs) have become popular alternatives (Edgington & Onghena, 2007; Good, 2005; Manly, 1997). PTs constitute a set of distribution-free statistical tests that calculate the probability of getting a value as extreme or more extreme than an obtained value of a test statistic under a null hypothesis by recalculating the test statistic for all or many rearrangements or divisions of the data. When all possible permutations of the data are exhaustively listed, the relevant PTs are often called *systematic* PTs. When the total number of permutations is too large, *random (Monte Carlo)* PTs are usually carried out. These tests use only a subset of all possible data permutations to approximate the *p* value (Dwass, 1957; Edgington & Onghena, 2007; Manly, 1997). Although some researchers (e.g., Edgington & Onghena, 2007; Kempthorne & Doerfler, 1969) suggested distinguishing tests on designs with random assignment from those without random assignment by calling them "randomization tests" and "permutation tests", respectively, we choose not to make this distinction in this review. PTs do not depend on a specific error distribution, and they use the original values of the data instead of the ranks. PTs were proposed in the early twentieth century, but were not widely used until much later. This is mostly because (a) they were too computationally intensive, (b) their applicability was limited to simple scenarios, (c) and they could be replaced by the available classical nonparametric tests based on ranks (Welch, 1990).

Now PTs are experiencing a renaissance with the emergence of cheap and fast computers and applicable software, and with methodological and statistical advancements, making them applicable in a variety of experimental designs in many disciplines (Good, 2005). However, a general overview of the theoretical development and applications of PTs in the educational and behavioral sciences is still lacking, mainly because articles on PTs are spread out over the literature. Accordingly, a systematic review is called for.

The specific objectives of this article are:

1. to provide an overview of the theoretical development of PTs and summarize several key areas of theoretical research;

2. to summarize active areas of educational and behavioral research applying PTs;

3. to identify relevant types of analysis under which PTs have been applied; and

4. to offer articles included in this systematic review as exemplars for educational and behavioral researchers to carry out PTs in their own research.

First, we present the methods of our systematic literature search. Next, we summarize the results of the search for research papers in the educational and behavioral journals for the period 1989-2011[1]. In order to trace the theoretical development of PTs as well as to summarize their applications in the educational and behavioral research, journal articles

[1] This time frame is arbitrary. We started this review in 2009 and wanted to give a 20-year overview. While we were working on the review, additional interesting publications appeared and we added them in the review until 2011.

identified in the search are divided into two categories: theoretical articles and application articles. For the theoretical articles, we identified several key research areas. For the application papers, we identified several active application areas in the educational and behavioral sciences as well as several relevant types of analysis under which PTs are applied. Finally, we discuss the implications of our results and give several recommendations for future research.

Methodology

Systematic search process

We searched ERIC and Web of Science to identify the relevant literature. More specifically, we aimed to include in our study all articles on permutation or randomization tests, or reporting on studies using these tests, that are published between 1989 and 2011 in English-language journals in the field of educational and behavioral sciences[2]. The Appendix presents the details of our search strategy.

Study selection

The selection, based on title and abstract, was done by two review-authors. Articles that do not focus on PTs, are not published in journals, or use PTs in other disciplines were identified and removed from the search results. The two review-authors independently assessed those articles for inclusion. Inter rater agreement was calculated by dividing the number of agreements by the number of agreements plus disagreements. The inter rater reliability was 97.82%. Disagreements were resolved by discussion.

Afterwards, all selected articles were classified into two groups: a theoretical group and an application group. In this way, we intend to summarize the theoretical evolution of

[2] The identification of whether a journal is an educational or behavioral journal is achieved by looking at the journals in the ISI categories related to educational and behavioral sciences or to look at the aims and scope of the journals.

PTs, and the active areas and relevant types of analysis under which these methods have been applied.

In order to make the correct classification, all selected articles were read completely with the following questions in mind:

- Is the article focusing on the theoretical development of PTs? If so, which aspects of PTs are discussed?
- Is the article an application paper? If so, what is its research area in the educational or behavioral research field? In addition, the “data analysis” sections were scrutinized in order to determine the types of analysis under which PTs were carried out.

Data extraction and management

Data were extracted on:

- Author(s), year of publication, and journal
- Classification of articles (theoretical or applied)
- Categories of studies (for theoretical articles)
- Applied areas (for applied articles)
- Type of analysis (for applied articles)

Results

General description of search results

Our search strategy yielded 91 published articles from ERIC and 460 published articles from Web of Science. After removing the duplicate articles and excluding the articles that do not correspond to our inclusion criteria, we obtained 224 published articles (see Figure 1): 141 theoretical and 83 application articles.

Insert Figure 1 about here

The concrete results of the systematic review are illustrated for the “theoretical” and “application” papers separately.

Classification of theoretical papers

The 141 theoretical papers were grouped into six categories. The author(s) and publication year of the retrieved articles for each category are presented in Table 1. The number and percentage of articles for each category are presented in Table 2.

Insert Table 1 about here

Insert Table 2 about here

In the following, we summarize each category in more detail.

Articles introducing PTs. Papers belonging to this category serve pedagogical and introductory purposes. Although PTs are only discussed at an elementary level in these articles (except for Hunter & May, 2003), they play an important role in propagating PTs and their future applications in different disciplines. In many research articles, authors state that classical statistical methods such as two sample *t*-tests are often routinely applied, although in some situations they are problematic, for instance when parametric assumptions (e.g., normally distributed population) are violated. PTs are presented as good alternatives to parametric statistics. Papers in this category can acquaint the educational and behavioral researchers with some basic knowledge of PTs through concrete examples. At the same time, these didactical papers stress the importance of PTs and advocate integrating PTs into the traditional statistical curriculum.

Articles on algorithms, programs and software packages for PTs. The articles in this category show the methodological improvement of PTs in the educational and behavioral sciences. For example, Bakeman et al. (1996) introduced an algorithm about how to use Monte Carlo PTs for the analysis of behavior sequences. Hemelrijk (1990) proposed an algorithm on the use of PTs for the analysis of social interaction matrices, which can be applied to animal behavior analysis. Linting et al. (2011) introduced a technique on how to use PTs for components selection in principle component analysis (PCA). Long et al. (2010) proposed a PT to obtain probability values for chi-squared and likelihood-ratio test statistics for multiway contingency tables. Rounds et al. (1992) introduced PTs for evaluating vocational interest structural hypotheses. Besides new algorithms, articles in this section offer several ways of carrying out PTs through computers. These includes: (1) free available FORTRAN and R programs for specific applications (e.g., Berry & Mielke, 1996; Bulté & Onghena, 2008, 2009; Edgington & Khuller, 1992; Johnston et al., 2008), (2) stand-alone software packages for PTs (e.g., May et al., 1989), (3) and programs through general statistical packages, like SAS and SPSS (e.g., Cai, 2006; Chen & Dunlap, 1993; Hayes, 1998; O'Connor, 1999, 2006).

Articles on the performance of PTs. It has been argued that PTs have good operation characteristics as compared to parametric tests and standard nonparametric tests. Over the last two decades, due to the increment of computer processing speed, the amount of studies focusing on the performance of PTs has substantially increased. Our review includes 27 studies examining the performance of PTs. Researchers have compared the performance of PTs with both parametric and nonparametric rank test counterparts through a range of different scenarios. For instance, van den Brink and van den Brink (1989) compared the power of the *t* test, Wilcoxon's test and approximate PTs for the two-sample location problem. Peres-Neto and Olden (2001) evaluated the performance of permuted ANOVA, parametric ANOVA, and Kruskal-Wallis test for the data from behavioral studies. Mewhort (2005) compared the performance of PTs and *F* tests when the normality of error has been violated. Those studies can help researchers to choose the most appropriate tests for their own experimental settings.

Articles on multivariate PTs. All the above mentioned papers discuss univariate PTs and their performance. There is also a need for distribution-free alternatives for parametric multivariate tests (e.g., MANOVAs). Some researchers (e.g., Blair et al., 1994) suggest the use of multivariate PTs (MPTs) as possible alternatives to statistical inference for multivariate designs when the parametric assumptions, such as the sample populations are multivariate normal, cannot be met. We found 11 articles discussing MPTs issues. Most articles present the principles of MPTs (e.g., Blair & Karniski, 1993; Maris, 2004; Mielke & Berry, 1999) and their performance (e.g., Blair et al., 1994; Finch & Davenport, 2009; Yoder et al., 2004). Besides, Pesarin (1990) proposed a nonparametric combination of marginal dependent PTs. Abbate et al. (2001) extended this combination method to multidimensional situations.

Articles on PTs for single-case designs. When researchers design an experiment, a group design is often the first option. Although very useful, group designs have their limitations, for example in areas that involve very specific and rare types of participants (Edgington & Onghena, 2007). In these areas, single-case experimental designs can be a good alternative to group designs. When conducting statistical analyses for single-case designs, parametric statistical tests, such as *t* tests and ANOVAs, are often inappropriate. PTs are a preferred option compared to these parametric statistics. Articles in this category discuss PTs for single-case designs from several aspects. Some articles discuss how PTs can be applied to different single-case experiments, such as ABAB designs (e.g., Manolov & Solanas, 2008; Onghena, 1992), alternating treatments designs (e.g., Onghena & Edgington, 1994) and multiple-baseline designs (e.g., Ferron & Jones, 2006). Meanwhile, some articles focus on the performance (e.g., in terms of statistical power) of PTs for single-case experiments (e.g., Lall & Levin, 2004; Sierra et al., 2005).

Articles on advanced topics. Some other papers discuss theoretical problems of PTs at an advanced level. For instance, Mewhort et al. (2010) introduced a technique on how to apply PTs to factorial designs. Johnston et al. (2007b) discussed the issue on the number of permutations that is necessary to accurately estimate the *p* value. Long et al. (2007) proposed to use PTs for the estimation of the standard error instead of traditional asymptotic estimates. Mielke et al. (2004) examined a method to combine probability values from independent PTs. Takane and Hwang (2002) and Takane et al. (2008) examined PTs in canonical correlation analysis for testing the statistical significance of canonical correlations. Takane and Hwang (2005) discussed how to use PTs for dimensionality selection.

Classification of application papers

Our review includes 83 articles applying PTs in the educational and behavioral research. Table 3 shows some specific features of each application paper with respect to application areas and types of analysis.

Insert Table 3 about here

Most application articles have employed PTs for data analysis in four active areas. In the following, we summarize each area in more detail.

Vocational interests. Vocational interests, as expressions of personality, are a hot topic in psychological research. Holland's (1985) hexagon model is a popular method on investigating the career interests among individuals. In order to examine the fit of the Holland's circular order relations to any similarity or dissimilarity matrix (e.g., a correlation matrix), a PT for hypothesized order relationships (Hubert & Arabie, 1987) has often been applied. For this PT, the randomization distribution is generated through rearranging the rows and columns of the correlation matrix. For each rearrangement, the number of confirmed predictions of hypothesized order relations for this rearranged correlation matrix is calculated. The *p* value is the proportion of arrangements that can yield the same number of hypothesized predictions or more than that from the observed correlation matrix. This PT can be realized on the computer via a FORTRAN program, RANDALL (Tracey, 1997). We retrieved 19 applications of PTs in the evaluation of the circular order relations in vocational interests (e.g., Anderson et al., 1997; Darcy & Tracey, 2007; Hedrih, 2008; Nagy et al., 2010; Šverko, 2008).

Animal behaviors. The study of animal behaviors is another area in which PTs have been widely used in recent years. Among all retrieved articles in this category, a majority of them concentrated on the discussion of association among animals in a social structure. In those association studies, researchers try to test whether a certain preferred and/or avoided companionship can be explained as a random fashion (Bejder et al., 1998; Whitehead, 1999). A test of random association can be performed through the idea of permutation proposed by Manly (1997). Several articles from this review have taken this approach (e.g., Fujita & Higuchi, 2007; Lemons & Sedinger, 2011; Richardson et al., 2010; Sendova-Franks & Franks, 1995a, 1995b). Later, Bejder et al. (1998) described an updated permutation procedure, with a further modification by Whitehead (1999) for testing the randomness of association. Meanwhile, this algorithm can be realized through a computer program, SOCPROG (Whitehead, 2009). This method has been applied in three articles (Durrell et al., 2004; Ramos-Fernandez et al., 2009; Ramp et al., 2010).

Sometimes the examination of animal association involves multivariate data from groups or individuals. For instance, researchers may intend to assess whether or not birds close to one another have songs that are more similar than those pairs that are located further apart geographically (Schnell, Watt, & Douglas, 1985). Under this kind of circumstances, matrix permutation procedures (Hemelrijk, 1990; Mantel, 1967;) were often applied. With this procedure, two square distance or similarity matrices, each representing different characteristics for the same group or individuals, are compared to determine whether there is a statistical correlation between the corresponding elements. The test statistic is the sum of the products of corresponding matrix elements. After randomly reassigning rows and columns of one matrix, the test statistic is re-calculated. This process is repeated many times, and the null distribution can be generated. We found three articles using Mantel's test to test the association among animals (Mitani & Brandt, 1994; Mitani et al., 2000; Payne et al., 2000).

Brain and behavior. The relationship between brain and behavior is a hot study area in the contemporary psychological and behavioral research. The appearance of model imaging equipment such as MRT (magnetic resonance imaging) makes it possible to position certain cognitive activities associated with specific brain regions. As the statistical parametric mapping approach is not free from parametric assumptions, PTs are strongly recommended because they can be free from the distributional assumptions and deal with the multiple comparisons issue. For instance, PTs have been used to explore the early impact of antipsychotics on brain morphology (Chua et al., 2009) and to examine the relationships between regional activation and behavioral performance measures (Ng et al., 2011).

ERP (event-related brain potential) and EEG (electroencephalogram), as alternative tools on brain research, can provide direct, real-time measures of brain activity associated with successive stages of information processing (Kayser et al., 2007). PTs have proven useful for the comparison of topographies because they are free from distributional assumptions and are still valid even if the number of channels is larger than the sample size (Maris, 2004). For instance, PTs have been used to evaluate topographic old/new differences for paired samples (Kayser et al., 2007).

Gene and behavior. The relationship between gene and behavior is another hot study area in psychological and behavioral research. One of the topics in the study of the effect of genes is whether certain genetic markers are associated with relevant behaviors or diseases. The statistical testing of a marker-disease association analysis usually requires the simultaneous testing of multiple hypotheses, requiring an adjustment on the significance values in order to decrease the Type I error rate. PTs can be used to correct for multiple testing. The PT is performed by randomly assigning the genotypes across subjects with the phenotype variables unchanged so that any relationship between genotype and phenotype can be broken up. With each permutation, a chosen test statistic is re-calculated for the phenotypes. The empirical p value can be achieved by comparing the obtained test statistic to all the other test statistics across all data divisions forming the null distribution. Several articles in this review adopted PTs for multiple comparison on gene and behavior research (e.g., Arias-Vasquez et al., 2011; Lerer et al., 2010; Liao et al., 2009).

Types of analysis

In this section, we summarize the major types of analysis under which PTs have been applied in the educational and behavioral research. The number and percentage of each type of analysis is presented in Table 4.

Insert Table 4 about here

The studies on vocational interests often involve evaluating the fit of hypothesized order relations. By applying PTs of hypothesized order relatons, confirmatory examinations on order relations can be realized. In animal behavior research, PTs have been used to test the existence of social structures. With multivariate data for testing association of social structure, Mantel's randomization tests were often used to examine the correlation between two (or more) square distance matrices.

PTs have also been applied in multivariate designs. Relying on fewer assumptions, MPTs can be used in settings where the parametric MANOVA technique is not feasible (e.g., Kayser et al., 2007; Knyazeva et al., 2010). Moreover, providing more power than the classical Bonferroni method, multiple comparisons corrected by PTs have been widely employed in many studies on the relationship between brain and behavior as well as gene and behavior.

As mentioned above, the group approach of experimental designs is not always possible and single-case experimental designs might be good alternatives. PTs are particularly useful for testing the statistical significance in those single-case studies (e.g., Bardon et al., 2008; Dennin & Ellis, 2003; Huang & Chao, 1999; Koene, 1996; Regan et al., 2005; Ross & Begeny, 2011).

In addition, PTs can be employed in independent two-group designs (e.g., Greeff & Conradie, 1998; Longenecker et al., 2010; Woodruff et al., 1997). Besides, PTs have also been applied under paired two-group designs (e.g., Boltri et al., 2003; Snyder et al., 2010). In a paired two-group design, subjects are tested before and after a treatment. Each measurement of the pretest is linked to one measurement of the posttest. This approach is valuable, particularly when independent two-group experiments are not feasible.

Discussion

Parametric statistical methods, such as standard *t* or *F* tests, are frequently used for hypothesis testing in educational and behavioral research. However, these tests require that the observations are randomly drawn from a normally distributed population, that the population variances are equal, and that the observations are independent of each other. An advantage of PTs is that they do not make any assumptions regarding the probability distribution underlying the data at hand. Additionally, PTs are very easy to apply and versatile, so that researchers can develop a PT for their own particular design (Edgington & Onghena, 2007).

Compared with classical parametric statistical methods, PTs are not frequently used by researchers. One of the reasons for this is probably that most statistical textbooks do not cover this topic. To further advance the development and applications of PTs, an introduction of PTs' rationale and advocating instruction of PTs in basic statistical training are desired. This review reveals that Lock and Lock (2008), Rossman (2008), and Tintle et al. (2011) have made initial efforts to introduce PTs in statistics education. Rodger's (1999) taxonomy gave a good introduction on how to teach sampling. However, more efforts needs to be done to make PTs a standard part like parametric statistical test in statistical curriculum.

It is fortunate to see from this review that the computing burden of PTs is reduced, not only by technological developments, but also by recent efforts of educational and behavioral researchers. For example, Mewhort et al. (2010) introduced a PT for a 2 by 2 factorial design, which decreases the computational load to a large extent. It is noted that the method of Mewhort et al. (2010) is based on Gill's (2007) algorithm. This algorithm can greatly reduce the computing load by using a Fourier expansion to count cases that are as extreme as, or more extreme than, the data observed. Besides new algorithms, educational and behavioral researchers have made their effort to popularize PTs by developing computer software and programs. These includes: (a) basic programming language such as FORTRAN (e.g., Berry & Mielke, 1996, 1998; Edgington & Khuller, 1992); (2) statistical programming language such as SAS (e.g., Chen & Dunlap, 1993), SPSS (e.g., Cai, 2006; Hayes, 1998), and R (Bulté & Onghena, 2008, 2009; Eudey et al., 2010); and (3) stand-alone software (e.g., Dixon et al., 1998; May et al., 1989; McKenzie et al., 1997; Onghena & May, 1995). However, it is unfortunate to see that most of the software and programs perform PTs under univariate designs and the facility to deal with multivariate PTs is still lacking. It is also noted that we are happy to see that parallel computing technique combined with high performance computing has begun to be employed in genetic research (Petrou et al., 2011). Although it only allows for the applications of PTs for multiple comparisons, we regard it as a revolution for PTs.

Meanwhile, methodological possibilities of PTs have been extended over the last 20 years. Research foci on PTs have shifted from basic rationale introduction to more advanced theories, from univariate to multivariate settings, and from simple applications to the possibilities of more complicated applications. Among those articles, a majority of them focused on algorithms and programs of PTs in different contexts, PTs for single-case designs, and performance of PTs for group designs, whereas multivariate PTs were less discussed. Given the theoretical development, PTs have been employed in several active areas of educational and behavioral research and under certain types of experimental designs. It is exciting to see that PTs have begun to be applied in brain and behavior as well as gene and behavior research. In these two research fields, PTs were used to yield the corrected *p* values for multiple comparisons (e.g., Lerer et al., 2010; Liao et al., 2009; Savitz et al., 2008).

However, we also found that PTs were used under simple contexts (e.g., order relations; randomness analysis) in nearly half of the application articles (41 articles in total). To date, the applications of PTs in more complex contexts (e.g., multivariate designs) are still quite limited (3 articles in total).

As to the association between the theoretical and application articles, some applications of PTs can be attributed to the theoretical developments published in the educational and behavioral journals. In the area of vocational interests, PTs of hypothesized order relations have been applied to evaluate the fit of circular order models. The rationale and procedure of this PT were proposed by Hubert and Arabie (1987). This paper, although not included in our review due to its early publishing date, was published in a psychological journal. In the area of brain and behavior, MPTs have been used to make comparisons among topographies. The methods used in the articles were originated from the work by Pesarin (1990), Blair et al. (1994), and Blair and Karniski (1993), which were all covered in the theoretical part. Moreover, the applications of PTs for single-case studies in this review can also be attributed to the theoretical development of PTs discussed in the theoretical section.

Recommendations for future research

Based on the systematic review, we conclude that PTs have received great attention and have been applied in many educational and behavioral studies in the past 20 years but still need to be improved. In the following, we propose several topics that may further promote the development and applications of PTs:

1) More statistical curricula that integrate PTs as part of basic statistical training in the educational and behavioral sciences;
2) Reviews of PTs in other disciplines, so that an overall framework of PTs can be achieved;

3) New algorithms and programs of PTs for two-group, multiple-group, factorial, and multivariate designs based on parallel computing theory;
4) Multivariate PTs software and simulation studies on the performance of multivariate PTs;
5) An R package for PTs (univariate and multivariate PTs);
6) Internet and cloud computing based platform for PTs.

Conclusion

In this review, we discussed the theoretical developments and applications of PTs in educational and behavioral research. On the one hand, we categorized theoretical papers into six categories so that active theoretical developments can be clarified, which indicated the extension of the methodological possibilities of PTs over the past 20 years. On the other hand, main active application areas were summarized. It is good to see that (1) some researchers began to advocate introducing PTs into basic statistics training; (2) computing load for PTs may be reduced dramatically by some intelligent algorithms; (3) PTs began to be applied in new areas such as brain and behavior research and gene and behavior research; (4) besides simple types of analysis such as independent two-group comparison, PTs can also be carried out under more complex situations such as multivariate analysis. All the above information offers one important message: for many (even complex) parametric techniques based on distributional assumptions, alternative PTs can be used. Finally, we offered several recommendations for future research.

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Table 1

Categories of Theoretical Articles, Number of Articles for Each Category, and Articles in Each Category

Category and number of articles for each category	Articles in each category
Introduction to and instruction of PTs (13)	Bai and Pan (2008), Barbella, Denby, and Landwehr (1990), Bear (1995), Chin, Haughton, and Aczel (1996), Hunter and May (2003), LaFleur and Greevy (2009), Lock and Lock (2008), Maguire and Rogers (1989), May and Hunter (1993), Rodgers (1999), Rossman (2008), Tintle, VanderStoep, Holmes, Quisenberry, and Swanson (2011), and Utts (1989)
Algorithms, programs and software for PTs (54)	Bakeman, McArthur, and Quera (1996), Bakeman, Robinson, and Quera (1996), Bejder, Fletcher, and Brager (1998), Berry, Johnston, and Mielke (2005, 2008a), Berry, Johnston, Zahran, and Mielke (2009), Berry and Mielke (1992a, 1992b, 1994, 1996, 1997, 1998), Bilker, Brensinger, and Gur (2004), Buja and Eyuboglu (1992), Bulté and Onghena (2008, 2009), Cai (2006), Chen and Dunlap (1993), de Vries (1993,1995), Dekle, Leung, and Zhu (2008), Dixon, Woodard, and Merry (1998), Dunlap, Burke, and Smith-Crowe (2003), Edgington and Khuller (1992), Eudey, Kerr, and Trumbo (2010), Fischhoff, Dushoff, Sundaresan, Cordingley, and Rubenstein (2009), Gondan (2010), Hayes (1998), Hemelrijk (1990), Johnston, Berry, and Mielke (2008), Lapointe and Garland (2001), Legendre and Lapointe (1995), Linting, van Os, and Meulman (2011), Long, Berry, and Mielke (2009, 2010), May, Masson, and Hunter (1989), McKenzie, Mackinnon, David (1997), Medland, Schmitt, Webb, Kuo, and Neale (2009), Mielke and Berry (1994, 2000), Mundry (1999), Mundry and Sommer (2007), Neuhäuser and Manly (2004), Neuhäuser and Ruxton (2009), O'Connor (1999, 2006), Onghena and May (1995), Rounds, Tracey, and Hubert (1992), Stahl (2004), Tan, Imbos, and Does (1994), Sundaresan, Fischhoff, and Dushoff (2009), Tracey (1997), Vera, Heiser, and Murillo (2007), and Whitehead (2009)
Performance of PTs (27)	Adams and Anthony (1996), Beasley, Erickson, and Allison (2009), Berry, Johnston, and Mielke (2003, 2008b, 2011), Berry, Mielke, and Mielke (2002), Camilli and Smith (1990), Campbell, Legendre, Lapointe (2009), Dekker, Krackhardt, and Snijders (2007), Dunlap (2003), Groppe, Urbach, and Kutas (2011), Hayes (1996), Hayes and Cai (2007), Kimberg,

	Coslett, and Schwartz (2007), Krause et al. (2009), Lapointe and Legendre (1995), Lunneborg (2001), Medina, Kimberg, Chatterjee, and Coslett (2010), Mewhort (2005), Mewhort, Kelly, and Johns (2009), Mielke and Berry (2002), Myors (1998), Oden and Sokal (1992), Peres-Neto and Olden (2001), van den Brink and van den Brink (1989), Whitehead (2008), and Zumbo (1996)
Multivariate PTs (11)	Abbate, Giogianni, Munao, Pesarin, and Salmaso (2001), Blair, Higgins, Karniski, and Kromrey (1994), Blair and Karniski (1993), Finch and Davenport (2009), Maris (2004), Mielke and Berry (1999, 2007a), Mielke, Berry, and Neidt (1996), Pesarin (1990), Yoder, Blackford, Waller, and Kim (2004), Yoder, Bruce, and Tapp (2001)
PTs for single-case designs (22)	Edgington (1996), Ferron and Foster-Johnson (1998), Ferron, Foster-Johnson, and Kromrey (2003), Ferron and Jones (2006), Ferron and Onghena (1996), Ferron and Sentovich (2002), Ferron and Ware (1994, 1995), Fisch (2001), Haardörfer and Gagné (2010), Kratochwill and Levin (2010), Lall and Levin (2004), Levin and Wampold (1999), Levin, Lall, and Kratochwill (2011), Manolov and Solanas (2008, 2009), Manolov, Solanas, Bulté, and Onghena (2010), Onghena (1992), Onghena and Edgington (1994), Perdices and Tate (2009), Sierra, Solanas, and Quera (2005), and Solanas, Sierra, Quera, and Manolov (2008)
Advanced topics (14)	Dzhafarov, Ünlü, Trendtel, and Colonius (2011), Johnston, Berry, and Mielke (2007a, 2007b), Lix and Sajobi (2010), Long, Berry, and Mielke (2007), McKenzie, Onghena, Hogenraad, Martindale, and MacKinnon (1999), Mewhort, Johns, and Kelly (2010), Mielke, Berry, and Johnston (2004), Mielke, Johnston, and Berry (2004), Prelog, Berry, and Mielke (2009), Takane, Hwang, and Abdi (2008), Takane and Hwang (2002, 2005), and Verboon (1993)

Table 2

Number and Percentage of Theoretical Articles by Research Categories

Research categories	**Number**	**Percentage**
Introduction to and instruction of PTs	13	9.2
Algorithms, programs and software for PTs	54	38.3
Performance of PTs	27	19.2
Multivariate PTs	11	7.8
PTs for single-case designs	22	15.6
Advanced topics	14	9.9
Total	141	

Table 3

Classification of Application Articles: Active Areas of Application and Types of Analysis

Areas of application/type of analysis	**Article**
Vocational interests (19 articles in total)	
Order relations (19)	Anderson, Tracey, and Rounds (1997), Darcy and Tracey (2007), Day, Rounds, and Swaney (1998), du Toit and de Bruin (2002), Einarsdóttir (2002), Fouad (1997), Glideen-Tracey and Greenwood (1997), Glidden-Tracey and Parraga (1996), Hedrih (2007), Hofsess and Tracey (2005), Leong, Austin, Sekaran, and Komarraju (1998), Long and Tracey (2006), Nagy, Trautwein, and Lüdtke (2010), Rounds and Tracey (1996), Ryan, Tracey, and Rounds (1996), Šverko (2008), Tracey and Rounds (1994), Tracey and Ward (1998), and Yang, Stokes, and Hui (2005)
Animal behavior (24 articles in total)	
Randomness analysis (19)	Avilés, Varas, and Dyreson (1999), de Vries, Steven, and Vervaecke (2006), Durrell, Sneddon, O'Connell, and Whitehead (2004), Franks, Sendova-Franks, and Anderson (2001), Fujita and Higuchi (2007), Kennedy, Spencer, and Gray (1996), Lemons and Sedinger (2011), Miller, Shapiro, Tyack, and Solow (2004), Mitani and Amsler (2003), Ramos-Fernandez et al. (2009), Ramp, Hagen, Palsbøll, Bérubé, and Sears (2010), Ribi and Porter (1995), Richardson, Ewen, Amstrong, and Hauber (2010), Roberts and Evans (1993), Sendova-Franks and Franks (1995a, 1995b), Trainer, McDonald, and Learn (2002), Verdolin and Slobodchikoff (2009), and Williams and Thomson (1998)
Single-case analysis (1)	Koene (1996)
Proximity matrices (3)	Mitani and Brandt (1994), Mitani, Merriwether, and Zhang (2000), and Payne, Woods, Siddall, and Parr (2000)
Multivariate analysis (1)	Normando, Corain, Salvadoretti, Meers, and Valsecchi (2009)

Brain and behavior (9 articles in total)	
Multiple comparisons (4)	Apostolova et al. (2008), Chakrabarti, Bullmore, and Baron-Cohen (2006), Chua et al. (2009), and Dineen et al. (2009)
Multivariate analysis (1)	Kayser, Tenke, Gates, and Bruder (2007)
Repeated-measure analysis (1)	Knyazeva et al. (2010)
Regression & correlation (2)	Ng, Cooper, Williams, Bullmore, de Zubicaray, and Suckling (2001) and Ridler et al. (2001)
Independent two-group comparison (1)	Woodruff et al. (1997)
Gene and behavior (12 articles in total)	
Multiple comparisons (11)	Arias-Vasquez et al. (2011), Chakrabarti et al. (2009), Hahn et al. (2008), Lerer et al. (2010), Liao et al. (2009), Savitz, van der Merwe, and Ramesar. (2008), Wright, Butlin, and Carlborg (2006), Yue et al. (2011), Zhang et al. (2005), Zhao et al. (2009), and Zheng et al. (2011)
Regression & correlation (1)	Ferraro et al. (2011)
Educational psychology (7 articles in total)	
Single-case analysis (5)	Bardon, Dona, and Symons (2008), Dennin and Ellis (2003), Huang and Chao (1999), Regan, Mastropieri, and Scruggs (2005), and Ross and Begeny (2011)
Randomness analysis (2)	Goldstein, Arnold, Rosenberg, Stowe, and Ortiz (2001) and Kessler and Treiman (2001)
Neuropsychology (6 articles in total)	
Proximity matrices (1)	Brusco (2004)
Regression & correlation (1)	Carlier, Beau, Marchaland, and Michel (1994)
Multivariate analysis (1)	Fehr, Wiedenmann, and Herrmann (2007)
Independent two-group comparison (1)	Longenecker, Kohn, Liu, Zoltick, Weinberger, and Elvevag (2010)
Single-case analysis (2)	Samuel et al. (2000) and Sunderland, Walker, and Walker (2006)
Multidisciplinary psychology (3 articles in total)	

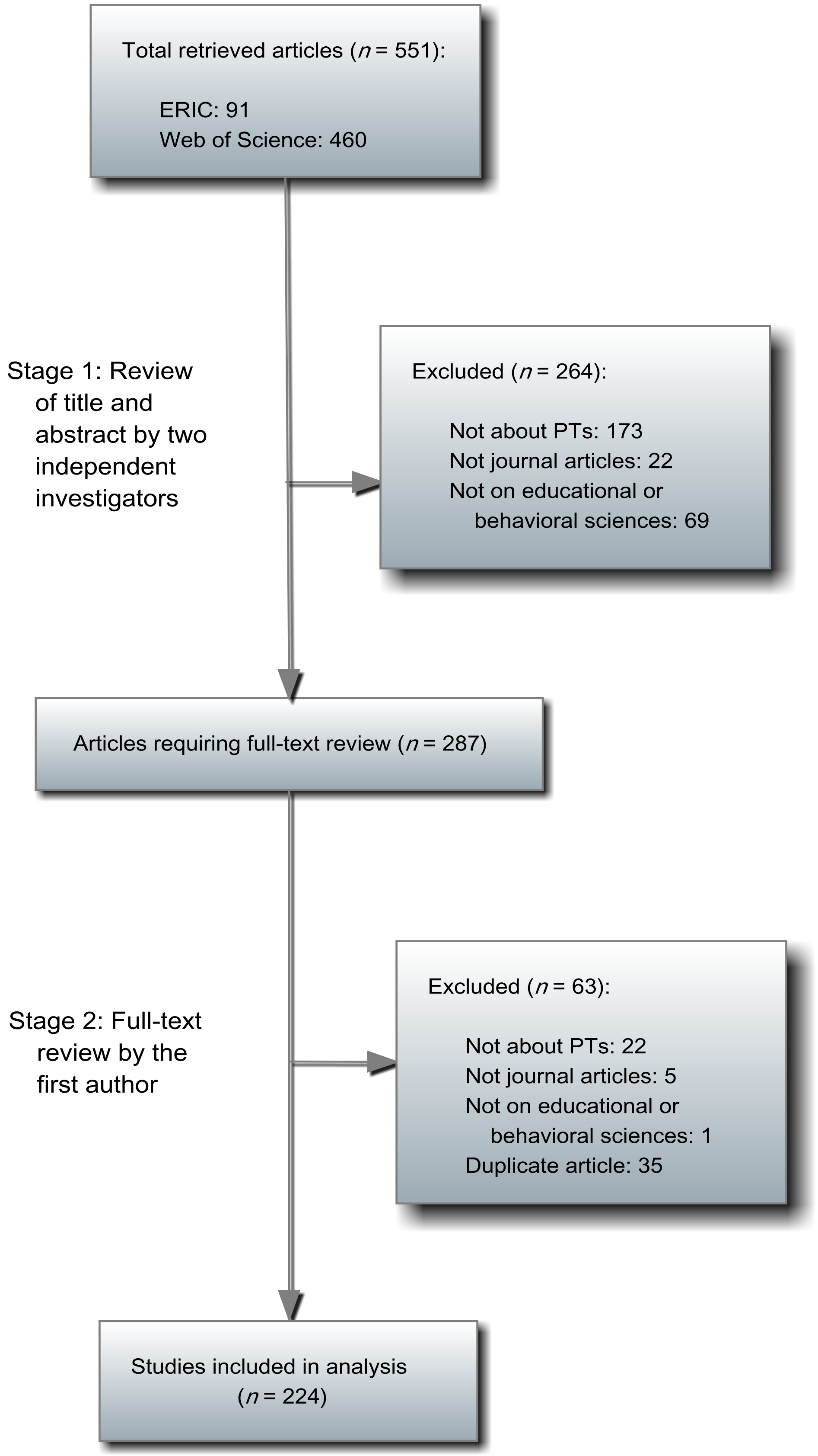
Independent two-group analysis (2)	Greeff and Conradie (1998) and Spilková and Hochel (2009)
Randomness analysis (1)	Gutierrez-Garcia and Tusell (1997)
Education research (3 articles in total)	
Paired two-group comparison (2)	Boltri, Hash, and Vogel (2003) and Snyder et al. (2010)
Independent two-group comparison (1)	Kline (1991)

Table 4

Number and Percentage of Application Articles by Relevant Types of Analysis

Statistical methods	**Number**	**Percentage**
Independent two-group comparison	5	6.2
Paired two-group comparison	2	2.5
Regression & correlation	4	4.9
Repeated-measures analysis	1	1.2
Multivariate analysis	3	3.7
Multiple comparisons	15	17.3
Single-case analysis	8	9.9
Proximity matrices	4	4.9
Order relations	19	23.5
Randomness analysis	22	25.9
Total	83	

Figure 1. Study flow diagram.



Appendix: Search Strategy

ERIC Search

“randomization test*” OR “randomisation test*” OR “permutation test*”

Limits: English, journal articles, timespan (from 1989 to 2011)

Total number of citations: 91

Web of Science Search

Stage 1: Topic = (randomization test*) or Topic = (randomisation test*) or Topic = (permutation test*) Refined by: Document Type = (ARTICLE) and Language = (ENGLISH) Databases = SCI-EXPANDED, SSCI, A&HCI Timespan = (from 1989 to 2011)

Total number of citations: 7281

Stage 2: Afterwards, we refined the total 7281 articles by: Web of Science Categories = (Mathematics interdisciplinary applications) OR (Psychology Experimental) OR (Behavioral sciences) OR (Psychology multidisciplinary) OR (Psychology mathematical) OR (Psychology applied) OR (Psychology developmental) OR (Psychology) OR (Social sciences mathematical methods) OR (Psychology clinical) OR (Multidisciplinary sciences) OR (Psychology educational) OR (Education educational research)

Obtained number of citations after the second stage: 460