A CALL TO ACCOMPANY PRE-REGISTRATION WITH MEANS TO FULL,
EFFECTIVE AND HONEST EXPLORATION

A call to accompany pre- registration with means to valuable and effective exploration

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Abstract

Harking and p-hacking are considered as main causes of the replication crisis, and pre-registration of hypotheses and analyses is regarded as the best countermeasure so far.

However, the pressure to produce purportedly confirming results through hidden exploration largely resists. While some pre-registration advocates encourage the alternative of honest and comprehensive explorative research, others accuse pre-registration of harming exploration.

We argue that researchers must be equipped with competencies on *valuable* exploration if pre-registration is to become mainstream and exploration is to be freed from its narrowed and flawed purpose. We discuss what valuable exploration should be: honest, as full as necessary (especially in new research domains) and as efficient as possible (resulting in only few and presumably true new hypotheses). After discussions on methods for filtering explorative results and pre-registration we end with a short research agenda on exploration and proposals for implementation to stakeholders (peer-reviewers, journal editors and funding agencies) who have the means both to enforce pre-registration and to provide room for valuable exploration. For example, we propose that yet a study abstract must contain separated lists of confirmatory results and new hypotheses obtained from exploration.

Keywords

Exploration, confirmation, filtering, smoothing, pre-registration, replication, editors, reviewers

Introduction

Hidden exploration is a cause of the replication crisis

P-hacking and harking misuse exploration for confirmation purposes and are regarded as two proximate causes of the replication crisis (Head et al., 2015; Lewandowsky & Oberauer, 2020). The term *p*-hacking refers to the non-transparent trimming and reporting of analyses to support the desired hypothesis, whereas harking denotes the generation of a hypothesis “after the results are known” (Kerr, 1998). Evidence from self-reports (John et al., 2012; Kerr, 1998) and content-analysis (Woo et al., 2017) suggests that *p*-hacking and harking are common. The underlying ultimate cause is probably the pressure to produce purportedly confirmative results in the current incentive system (Gonzales & Cunningham, 2015; Kerr, 1998; McIntosh, 2017; Nosek & Lindsay, 2018; Nosek et al., 2018; Wagenmakers et al., 2012). Still, the number of publications and citation counts (and the volume of acquired third-party funding) dominate the course of academic careers although alternative assessments of scientific achievement are starting to emerge (for an overview, see Leising et al., 2020). The pressure to present confirmative results appears to be a direct consequence of publication bias toward positive findings (by itself considered as another cause of the replication crisis; Lewandowsky & Oberauer, 2020). This bias seems strongly influenced by the flawed desideratum to get what was expected before an investigation (Kerr, 1998). It sharply contradicts the Popperian hypothetico–deductive paradigm according to which failed trials of confirmation actually promotes scientific progress more (Glass & Hall, 2008; Kerr, 1998; Klayman & Ha, 1987; Locke, 2007). (In the following we use the shortened term “confirmation” for trials of confirmation.)

Pre-registration alone falls short to solve the problem

As long as it seems impossible to change the incentive system, pre-registration has been argued to be the most promising mode of intervention (Heers, 2020; Wagenmakers et al.,

2012). The paper format of pre-registered reports goes a step further and addresses publication bias through the guarantee of publication before the results are known (Allen & Mehler, 2019). Indeed, first analyses show much higher proportions of non-confirming results (Allen & Mehler, 2019; Scheel et al., 2020). However, major non-compliance issues in pre-registered reports have been reported like the failure to provide the study protocol or the final report (Claesen et al., 2019; Hardwicke & Ioannidis, 2018). Moreover, it is difficult to eliminate all degrees of freedom by pre-registering an analysis (Bian et al., 2020; Claesen et al., 2019). Anyway and encouraged by a growing number of journals that publish pre-registered reports (Chambers, 2019; Kupferschmidt, 2018; Nosek & Lindsay, 2018) and open science initiatives (Claesen et al., 2019), some suggest that pre-registration may become dominant in the future (Nosek & Lindsay, 2018).

Nonetheless, only a minority of psychological researchers seems to use any kind of registration so far. Moreover, pre-registration has been accused of harming exploration by eliminating the necessary flexibility in hypothesis formulation (Hollenbeck & Wright, 2017) and data analysis (Goldin-Meadow, 2016; Scott, 2013).

A culture of valuable exploration must evolve

Several researchers have already called for a major up-valuing of exploration as *a complement* to confirmation (Gonzales & Cunningham, 2015; McIntosh, 2017; Nosek et al., 2018). In this respect, Hollenbeck and Wright (2017) suggest to distinguish between “Sharking” (unhonest exploration through “secretly HARKing in the Introduction section”) and “Tharking” (honest exploration, “transparently HARKing in the Discussion section”). But the reality of very rare exploration denoted as such suggests that these calls are insufficient.

We argue that, in addition, researchers must be equipped with *competences* on what constitutes valuable exploration and how to conduct it. Otherwise, pure uncertainty might prevent them from abandoning the ritualised (Gigerenzer, 2018), almost obsessive, restriction

to confirmatory research. Within the prevailing incentive system, the promotion of competencies in exploration is a remaining means to counteract the pressure to produce nominally confirmatory results.

Aim of this paper

After summarizing the widespread blending of confirmation and exploration we discuss how to resolve it through the alternative track of exploration and conceptualize what valuable exploration constitutes in terms of honesty, completeness, and efficiency. We propose a conceptual framework to filter the signals out of the noise in data for coming up with fruitful new hypotheses and discuss the value of pre-registration of exploration. We end with an outline of a research agenda to elaborate on exploration and with suggestions to stakeholders to promote exploratory research.

The blending of confirmation and exploration and the proposed twin-track approach

Reasons for blending

There seem to be four major reasons for blending confirmation and exploration. Besides the pressure to present almost any analysis as confirmatory, psychological studies are meaningfully placed on a continuum between purely exploratory (“where the hypothesis is found in the data”) to purely confirmatory (“where the entire analysis plan has been explicated before the first participant is tested”) (Wagenmakers et al., 2012). This fits with the common experience of unexpected problems in messy data.

Then, the same method, statistical tests, is used for both confirmatory and exploratory purposes. This is indicated by the frequent finding of a small number of reported hypotheses but a high number of reported test results (Gigerenzer & Marewski, 2015). Finally, the blending continues through impaired scientific communication. Recipients of a purportedly

confirmative result build their research on the false assumption of true confirmation; or, if sensitive to the problem, do not know for sure whether a conclusion grounds on confirmation or mere exploration.

Science has been argued to be most productive if confirmation and exploration co-exist in a “good balance” but harking and *p*-hacking hinder an evaluation of their true proportions (Woo et al., 2017). Specification curves (Simonsohn et al., 2020) attempt to resolve this blending through making all possible explorative steps in confirmation transparent and, thus, describe the continuum between the two approaches to data analysis.

The blending is not fully solved by pre-registration

The only way to achieve a strict distinction between confirmation and exploration seems to be pre-registration. Otherwise, the choice of hypothesis and/or analysis could be influenced by inspecting the data (Heers, 2020; Wagenmakers et al., 2012), and pre-registration is the only mode of control on this so far (Lakens, 2019).

In summary of the above, there seem to be four remaining problems with pre-registration:

1. Still too few researchers use it
2. Their use is subject to major compliance problems
3. The persisting pressure to produce nominally confirmatory results (less but also in pre-registered reports)
4. Any exploration is down-valued if only pre-registered studies find acceptance.

3. - 4. call for the new culture of appreciating exploration. In order to address also 1. and 2., revaluing, elaborating and teaching exploration have to accompany attempts to make pre-registration mandatory for confirmatory studies. If the pressure (3.) maintains, any stricter rule on the implementation of pre-registration might just increase the effort in malpractice (2., Yamada, 2018). A simple instance is the possibility to use pre-registration but publish a

study's results only if they turn out to be confirmative. In this case, the fact that pre-registration has been done is mis-used to nominally increase the credibility of the results *post-hoc*, but a non-confirmative result would never make it to the public.

The complementary track of valuable exploration

Pre-registration aims to remove any explorative ingredient from confirmation, but at the same time the benefits of exploration as a full-value complement must be highlighted. Otherwise, exploration as the main source to *create new hypotheses* (Lakens, 2019) remains largely unused. We use the term “exploration” in the sense of this purpose and emphasise the following: exploration, honestly denoted as exploration, cannot be wrong, because it does not make a false assertion about whether a hypothesis is true or not, it just *proposes a new hypothesis* to be confirmed or disconfirmed in other data.

Revaluing such exploration would devalue harking and *p*-hacking through reducing the pressure of confirmation. A culture of comprehensive and honest exploration would free exploration from its narrowed and flawed scope of producing seemingly successful confirmation by only using as many degrees of freedom as necessary to shamefully achieve a desired conclusion; in terms of specification curves, to pick a fitting set of analysis options. On the contrary, *full exploration* may use all degrees of freedom in order to find anything of substantive interest that might be hidden in the data (Dirnagl, 2020). Stebbins (2001) adds the psychological benefit that with transparent exploration “the researcher is now a true amator of his or her work”. Vice versa, he points out, if exploration becomes more attractive, it can be reported more openly.

Relation with Popperian deduction

The twin-track approach builds on the common ground of Popperian deduction. Researchers can just stick with their confirmative research provided that they pre-register properly.

However, the approach emphasizes that Popper's "starting from anywhere" to raise a hypothesis (Klayman & Ha, 1987) includes starting from exploration. The reference to Popper reminds of the misguided desideratum of verification and the insight that falsification reveals errors in assumptions and triggers modification in those assumptions and perhaps the quest for something entirely new (Klayman & Ha, 1987).

The twin-track approach also seems to be in line with Lakatos' conception of science, according to which new additions from exploration contribute to the further development of theory (Lakatos, 1977).

One is allowed to use the same data twice if this is honestly communicated

The principle of *full exploration* includes that nothing should be excluded beforehand what may move science forward. However, recommendations such as the following could be misunderstood to mean that it is forbidden to use the same data for confirmation *and* exploration: "The interpretation of common statistical tests in terms of Type I and Type II error rates are valid only if the data were used once and if the statistical test was not chosen on the basis of suggestive patterns in the data" (Wagenmakers et al., 2012). Actually, exploration must not be used *before* confirmation, but it may well be used *later* to increase a confirmed or to decrease a non-confirmed hypothesis' severity (Lakens, 2019). Double use in this temporal order is established practice in medical research, for instance, when re-analysing consort data from the UK Biobank (2020) in a transparent way after the confirmatory results have been published.

In case of non-confirmation of, say the assumed effect of an intervention, a researcher might go on with common practices like subgroup analysis ("Is the intervention effective in females?"). This may lead to valuable insight and is not wrong as long as a result is not presented as a conclusion ("The intervention is effective in females."), but as a *newly formulated* hypothesis to be yet confirmed with new data ("We suggest that the intervention

may be effective in females.”). Such exploration, if honestly communicated, also offers a way out of the presumed fear of non-confirmation (“All my work was in vain if I fail to get my hypothesis confirmed!”). Likewise, in case of successful confirmation, it is allowed to proceed exploratorily in order to *refine* a hypothesis, for instance by increasing its severity (“We suggest that the intervention effect is greater than Δ .”).

What is valuable exploration?

This question has hardly been posed in psychology with rare exceptions (Behrens, 1997; Dirnagl, 2020). If this is not elaborated, uncertainty will keep researchers off the exploratory track and hinder the acceptance of exploratory research by others. If hypotheses are not raised according to accepted methodical standards, researchers may hesitate to spend their resources for confirmation attempts.

Full exploration

Valuable exploration should in the first place be *full exploration*; that is, consider *all* degrees of freedom in analysis and the entire variation in data to raise their full potential and to identify anything of substantive value that has previously been unknown or may question prior beliefs (Stebbins, 2001; Swedberg, 2018).

In soft sciences like psychology, the observed phenomena are probably caused by very complex processes that create large variation. Variation might occur across several abstraction levels, for example, the onset of a disorder may vary on variables describing the society, groups of individuals, individuals, time, life circumstances, personality dimensions, physical entities, brain voxels and circuits, neurons and molecules. On each of these levels there might be variation useful to explain why a disorder emerges.

Effective exploration

Research is always restricted to collect data only on a few levels, wherefore exploration needs to focus on levels where important variance is assumed to occur and could be explained for example, a behavioural outcome at the level of persons. This addresses the *efficiency* of exploration.

With “effective” we mean that exploration should advance science with new insights and not bother other researchers with hypotheses whose subsequent (non-)confirmation would waste resources and disturb scientific communication. This includes pointless confirmation trials and blind alleys of theory building. Thus, new hypotheses should be (1) true and (2) relevant. (1) aims to separate signals from noise, while the purpose of (2) is excluding proposals of modest scientific value for the benefit of *severe* hypotheses (Lakens, 2019); that is, if true, they move science considerably forward. Note that, as long as questionable research practices persist, assessing both (1) and (2) is hindered through dishonest scientific communication. Also note that there is an important alternative to (2): A wrong hypothesis might trigger true insights and thus anyway promote scientific progress (Nosek et al., 2018; Stebbins, 1992; Stebbins, 2006). An example is ego depletion, a severe instance of non-replication (Lurquin & Miyake, 2017), that has spawned the idea and finding that willpower is not a limited resource (Job et al., 2010). But this track to fruitful new insights seems outside of the scope of systematic exploration since such hypotheses may emerge from anywhere, not just from spurious data patterns.

Smoothing towards effective exploration

The more a field is already understood, the better an exploratory search can be structured by reducing the number of observed patterns that could lead to new hypotheses which then might turn out to be false. This involves not only the choice of the abstraction level (e.g. genomic loci) but also assumptions about how strongly an outcome (e.g. epigenetic response to stress exposition) varies across them. In this case, it seems advisable to use prior knowledge like

that the spatially closer two gene loci are, the more they share an association with an outcome (Jaffe et al., 2012).

Statistically, data patterns are reduced through *smoothing* (also known as regularization) methods. These address the noise, the seemingly signals, that can be found in any data. We pick up the conception of Greenland (2006) to reduce noise when conducting exploration while preserving latent structures through avoiding over-smoothing. This is illustrated with the fictive example in Figure 1, where we assume that an outcome $\mathbf{Y}$ varies across genomic loci ($\mathbf{X}$) along their relative spatial location (scaled from 0 to 100 here). The red line displays how $\mathbf{Y}$ truly varies across space $\mathbf{X}$ ($\mathbf{Y} = \sin(\sqrt{\mathbf{X}}) * 10 * \mathbf{X}$). We further assume that other factors contribute to $\mathbf{Y}$ through adding a residual with normal distribution (expectation = 0, standard deviation = 500). For smoothing we use cubic splines (command *twoway lpoly* in Stata 15.2, StataCorp, 2017) with different degrees of smoothing.

a. Free variation in x, no smoothing
- true function

b. moderate smoothing
- true function

c. strong smoothing
- true function

d. over-smoothing, linearity assumed, latent structure destroyed
- true function

Legend of Figure 1

The figure illustrates fictive data where an outcome **Y** varies across genomic loci (**X**) along a spatial position. The true **Y-X** relation (red line) equals $Y = \sin(\sqrt{x}) * 10 * x$, where deviations from it arise from random error in a sample of $n = 50$ (normally distributed with expectation = 0 and standard deviation = 500). Plot (a) shows the results (blue peaks) if no smoothing is done, plots (b) through (d) apply different levels of smoothing, from insufficient smoothing (b) and adequate smoothing (c) to over-smoothing (d).

Figure 1a) illustrates the random pattern that emerges if no smoothing is performed. Several outcome manifestations (spikes) may be used to generate new (sets of) hypotheses while

neglecting the spatial dependency. Using moderate smoothing (Figure 1b) we are able to identify a rough course and might hypothesise that the outcome is highest if X ranges between 40 and 70. Stronger smoothing (Figure 1c) leads us close to the true function and allows to further hypothesize a local minimum around $X = 25$. However, if too much smooth is applied (Figure 1d), the latent structure is destroyed and core features of the true function underlying the outcome manifestations are overlooked. Methods to smooth psychological data include a range of techniques some of which have long been common in psychology: Cluster analysis and latent mixture models smooth over intra-individual heterogeneity, factor analysis smooths over heterogeneity across items/variables, robust regression smooths over extreme values, regularization methods in regressions smooth over too many predictors in too small data sets, etc. Note that many of these methods have a Bayesian interpretation with parameters translating into the degree of smoothing used, which renders them capable to express the according beliefs formally (Greenland, 2006).

However, much elaboration is needed for sound guidance on how to apply these methods: whether they do the right smoothing to the appropriate extent to efficiently generate new hypotheses in a research area.

Individual versus community-driven filtering

Smoothing is a means to filtering the signals out of the noise, and the methods can broadly be classified into individually- versus community-driven filtering. The above describes *individual-driven filtering*, where scientists themselves filter their results before coming up with new hypotheses in a publication. A popular other class of methods preserves (rather than smoothing patterns across space) the outcome manifestations, but accounts for the overall (“familywise”) type I error rate when conducting individual statistical tests; a common practice in genome-wide association studies (Marigorta et al., 2018).

The most universal individual filtering method, though, is *internal cross-validation*, because it can, in principle, be combined with any analytical method. Its key idea is splitting a large data set randomly into n subsets, and to repeatedly run an exploratory analysis in $n-k$ subsets while evaluating the performance of the previously fitted model with the remaining k subsets. Repeated and nested resampling reduce error, but there are many ways to do so (including procedures that also take analytical decisions before a final analysis, “tuning parameters” that regulate the level of smoothing, into account), and the question, which is most effective, seems still subject of investigation in machine learning (Xiong et al., 2020).

Note that not using any individual filtering method has led to a loss of confidence in some disciplines (e.g., candidate genes in personality psychology vs. genetic epidemiology; Jorgensen et al., 2009).

By contrast, *community-driven filtering* relies on the scientific public and is usually implemented through per-publication peer reviews. This includes external cross-validation, where researchers use their data to generate hypotheses and data from others to filter the true ones (such “independent replication” has been required by journals on genetic research 20 years ago; König, 2011). For efficient scientific communication in *scientific papers* we propose that individually-driven filtering should *precede* community-driven filtering. However, we also encourage creating more *public repositories*. These may contain many hardly filtered results, for instance, associations from “large scale studies” between many factors and outcomes (Pennycook, 2018; Thompson et al., 2020). Such repositories allow others to test their theories, wherefore it is advisable to provide many results (Greenland et al., 2004).

How many new hypotheses should be proposed?

A small number of new hypotheses does not only protect against random data patterns, but also takes care of the limited resources for confirmatory attempts in external filtering.

Likewise, the psychology of perception suggests to limit oneself to a few new proposals to avoid information overload (Buchanan & Kock, 2001).

We believe that, at least as long as research needs to shift towards open science practises, over-filtering is generally the smaller mistake than under-filtering, because a small number of raised hypotheses in a large space of exploration serves the trust in the findings and thus promote trials of confirmation.

Pre-registration of exploration

Trust in exploratively generated results emerges from *honest communication*. As for confirmation studies, pre-registration serves transparency, here transparency in the amount of exploration that has been done to come up with a new hypotheses or, generally, how much “meandering of the research process” (Dirnagl, 2020) has happened. This information is crucial for any reader attempted to try to confirm them.

Since the aim of exploration is to find the *unexpected* signals, there has been a controversy in epidemiology about whether an analysis plan should be pre-registered (e.g. Loder et al., 2010). We suggest that researchers should anyway do this (on top of pre-registering study methods, instruments, variable lists etc.), because this creates transparency at least *in the initial plan*. There are good reasons to depart from a plan (e.g. an algorithm for model building may result in a substantively meaningless model) but this in turn must be mentioned in a publication. Together with open data, recipients may verify that the initial plan did not work and do their own exploration and see whether they come up with the same new hypothesis.

Interestingly, one may pre-register the plain information that exploration is to be carried out, what counteracts wrong confirmative claims later on (Eric-Jan Wagenmakers in a talk 2020).

The interplay between honest exploration and confirmation, publication and communication

Increasing a hypothesis' severity through exploration

Let's go back to the possibility to strengthen a hypothesis' strength through exploration (Lakens, 2019). Suppose an intervention effect that has been confirmed (as pre-registered) to be > 0 . Data may also suggest that the effect is not only larger than 0 but has a of practical (e.g. clinical) relevance (if only testing effect > 0 the effect might be infinitely small and substantively irrelevant; Greenland, 2017). Given a point estimate for the effect of d (and other statistical information like sample size or standard error), how should Δ in a modified hypothesis (i.e., effect $> \Delta$, $\Delta > 0$) be chosen? Apparently $\Delta = d$ would be over-optimistic because the data provide just as much evidence for the effect to be $> d$ than for the effect to be $< d$ (and this disregards that having estimated a large d has led to hypothesis modification in the first place). To our knowledge, there is no solution yet to this rather simple example besides cross-validation. Methodical elaboration seems necessary to provide analytical solutions that could be directly used.

Concatenated exploration

If a further argument in Stebbins (1992) holds true, revaluation of exploration might already have considerable effects in the current incentive system of pure count of publications and citations. With "concatenated exploration" he denotes a cooperative strategy that pays off for all who participate in a "longitudinal research process". Such a process starts with exploration (or plain observation) and gives rise to a confirmation trial and subsequent studies with modifications (through new exploration) and/or new confirmation trials, further refinement and so on. A similar idea is mentioned in Behrens (1997) and Nosek et al. (2018).

Stebbins (2001) describes a range of sociological examples, where such a chain of research has advanced science including postpartum changes in women and the development of women's occupational aspirations across the lifespan. In psychology, concatenated exploration appears to describe the idea behind the very common trial-and-error for the development of any intervention (e.g. the history of origins of dialectic behavior therapy, Linehan & Wilks, 2015). Besides, an interplay between exploration and confirmation has long been established practice in factor analysis, where the construction of a scale is a chain of setting up a model, testing it, modification, again testing, etc. (Hurley et al., 1997).

Impact on citation counts and career

Researchers who participate in such a chain of research publish at least once and can expect to be cited several times. In qualitative terms, they have a bigger chance of demonstrating confirmed findings in an application for an academic position and to be able to look back on research of enduring validity later in life.

Further research agenda for exploration

The following proposals are likely to give highly context-dependent answers and are therefore intended for separate consideration across the many fields and research quests of psychology:

1. Identify *domains* that appear promising for exploration.
2. Identify *levels* at which most relevant variation might occur.
3. Methodically elaborate on *what smoothing and what degree of smoothing* should be used. Recommendations should translate *smoothly* into substantive assumptions (e.g. how strongly brain activation might vary as a function of voxel distance): A minor change in assumptions should lead to only a minor change in the degree of smoothing and the resulting new hypotheses. Internal cross-validation may help where prior knowledge is sparse, but data is rich.

4. *Pre-register* an analysis that has been planned based on 1. – 3.

Recommendations to stakeholders

We end with a list of what stakeholders should do to establish good exploration in parallel with the obligation to pre-register (every non-registered hypothesis being considered as exploratory). With stakeholders we mean journal editors, peer-reviewers and funding agencies. These three groups have the largest means for change if they cooperate in addressing the following points. Funding agencies should provide financial incentives for reliable research, editors offer space and define rules that promote such research and reviewers should control compliance with them.

1. *Mandatory separation between tested versus new hypotheses* already listed in the abstract of an article.
2. *Compliance with pre-registration*: Editors should instruct reviewers (or associated editors) to check strictly that all claims on pre-registration equal what has actually been pre-registered (including pre-registration of exploration). Editors themselves might in turn check this, at least occasionally.
3. *Create new journal sections for explorative papers* to emphasize the value of the complementary explorative track and reserve space to this end (McIntosh, 2017; Thompson et al., 2020).
4. *Use editorials to mention gaps in theories* (Lakens, 2019) that could be filled by exploration (Woo et al., 2017).
5. *Invite distinguished scientists to provide good examples* of exploratory research (Woo et al., 2017).
6. *“Place exploratory analyses (regardless of the outcome) on citable public repositories”* (Pennycook, 2018; Thompson et al., 2020). Funding agencies are

requested to create more such space and fund studies to feed other researchers with their results in order to test previous theories and hypotheses and create new ones (Greenland et al., 2004).

7. *The common sense that every publication must have an introduction and a discussion part should be questioned.* Publications on observational data with association results appear most useful if they just describe the methods and provide their results (Greenland et al., 2004). This requires more acceptance of diversity in scientific skills. Researchers with different skills in data collection and data interpretation, for instance, should have according career tracks (Greenland et al., 2004).

Discussion

We have argued that exploration should be valued and freed from its grubby existence. The alternative of honest and effective exploration may reduce the pressure to do harking and p-hacking if researchers are equipped with competences to conduct such exploration. Yet teaching the insight how valuable exploration and true confirmation benefit from one another might contribute to improve the reliability of research.

Probably almost every reader of this article has been taught statistics and methods with a nearly exclusive focus on confirmation. Once a new generation of *two-trail* scientists will emerge, this generation might come up with powerful ways of cooperative exploration that our generation is incapable of imagining because of our confirmative priming.

We wish to conclude with the admittedly emotional remark that the necessity of writing this article on the *value of exploration in science* feels a bit odd. The self-evidence in the italic words may be reason enough to engage in veritable exploration and to look forward to a science thus multiply enriched.

Author Contributions:

Michael Höfler had the basic ideas for this manuscript, has elaborated on it and led the writing. Robert Miller and Stephan Scherbaum have contributed to the elaboration and have added further aspects and arguments (e.g. on filtering methods). Philipp Kanske has joined the writing in the final phase and has strengthened the structure and arguments from an outside perspective and made several contributions to the writing. All authors read and approved the final version of the manuscript.

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The authors declare that there were no conflicts of interest with respect to the authorship or the publication of this article.

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