

A systematic review of Null Hypothesis Significance Testing, sample sizes and statistical power in research using the Implicit Relational Assessment Procedure

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Following recent calls to examine the replicability of behavioral research, I examine two key determinants of replicability, sample sizes and statistical power, in research using the Implicit Relational Assessment Procedure (IRAP). A systematic review was used to gather all published studies employing the IRAP and extract their designs and sample sizes. The use of Null Hypothesis Significance Testing was found to be nearly ubiquitous, justifying the examination of statistical power. Using an established method, median sample sizes were used to estimate the statistical power to detect the average published effect size in psychological research ($r = .20$) in each year. Sample sizes and the statistical power they imply were found to be very low in IRAP studies (in 2022, median $N = 64$, power = .34). At the current rate of growth, the median study will only reach the recommended minimum power of at least .80 by 2080. The IRAP literature was directly compared with the Social and Personality psychology literature using an existing dataset. Median sample sizes and their implied statistical power were lower in the IRAP literature in all years than they were in Social and Personality psychology at the beginning of the Replication Crisis in 2011, and indeed in all subsequent years. Improvements in sample sizes and statistical power in the Social and Personality psychology literature were significantly and substantially larger than in the IRAP literature. Direct tests of the reproducibility and replicability of claims in the IRAP literature are needed.

Two seminal articles were published in 2011 whose implications the field of psychology is still grappling with. The first, by Daryl Bem (2011), contained literally impossible results about a supposed human ability to predict the future. It was remarkable not merely in its claims but because it employed modal research practices for the field to substantiate these conclusions. A second article by Simmons and colleagues (2011), coincidentally published around the same time as Bem (2011) but without any knowledge of his paper, demonstrated how our modal research practices can easily and routinely generate statistically significant results from what is actually just noise.

The fallout from this pair of papers and many more before and since is now a matter of history for some (e.g., for personal accounts see Gelman, 2016; Spellman, 2015). But their impact has been uneven and recognition of the Replication Crisis as a serious issue to be reckoned with has been heterogenous, both within and between fields. It would be too easy to dismiss the Replication Crisis as specific to Social and Personality psychology when other fields employ similar research practices. Over time,

recognition of these issues has spread to other areas of psychology (e.g., clinical psychology: Tackett et al., 2019) as well as a diverse range of other fields including cancer biology, economics, methodology, sociology, and philosophy (Baker & Dolgin, 2017; Boulesteix et al., 2020; Buckwalter, 2022; Gordon et al., 2020; Page et al., 2021).

These calls to take seriously the question of replicability have recently been echoed in the behavioral research communities. A recent editorial for *Perspectives on Behavior Science* characterized the situation well:

“Despite certain metatheoretical disputes (Burgos & Killeen, 2019), behavior science, behavior analysis, and psychology have much more in common than differences. Hence the ‘replication crisis’ in psychology could well be repeated in behavior science and behavior analysis. Even if it is not, it may hold some important lessons for both scientists and practitioners.” (Hantula, 2019, pp. 4-5)

Similarly, the Association for Contextual Behavioral Science’s Task force on the Strategies and Tactics of Contextual Behavioral Science Research (2021) recently announced its explicit support for Open

Science principles, including data transparency and a focus on replication. As such, there is now support for the idea that behavioral science, including component fields such as Behavior Analysis and Contextual Behavioral Science, would be enhanced by examining and enhancing the transparency and replicability of its findings.

In some ways, this could be seen as an appropriate return to our roots, from which we should never have departed. To take some positive examples of our field’s history here, whereas general psychology journals have until recently rarely published replication studies (Makel et al., 2012), behavioral journals such as the *Journal of Experimental Analysis of Behavior* and *Journal of Applied Behavior Analysis* have long history of publishing them. Behavioral research also has a long history of sharing research data (i.e., trial-level single case experimental design data being presented in tables and plots). Lastly, despite being written over 60 years ago, fully one quarter of Murray Sidman’s seminal behavioral textbook *Tactics of Scientific Research* (1960) is dedicated to discussion of the needs for replication studies, their taxonomy and function, and links between replication and generalization.

Replicability, sample size, and statistical power

Statistical power is the probability of detecting a true effect, and is synonymous with the sensitivity of a test and its False Negative Rate (Cohen, 1977). Low statistical power in original studies is a key contributor to the Replication Crisis in psychology (e.g., Asendorpf et al., 2013; Button et al., 2013; Munafò et al., 2017), with highly powered replications only obtaining the original finding in around one third to one half of studies depending on the definition of successful replication, and effect sizes observed in replication studies are typically only one-third the size of those in original studies (e.g., Ebersole et al., 2020; Klein et al., 2018; Open Science Collaboration, 2015). Journals that publish underpowered studies are likely to publish a greater proportion of conclusions that are false positives (Bakker et al., 2012; Ioannidis, 2005). As such, in reaction to the Replication Crisis in psychology, many have called for psychology research to employ higher powered tests and therefore larger sample sizes (e.g., Asendorpf et al., 2013; Button et al., 2013; Munafò et al., 2017; Wagenmakers et al., 2012).

Along with the False Positive Rate (i.e., α -level, typically $< .05$), statistical power is one of two key properties of inference via NHST that defines the long-run error rates of the inferences we make from data. Power is generally a less familiar concept than α level for many researchers, but it is so central to our ability to make inferences from data (Cohen, 1992). Nonetheless, for decades, statistical power remained very low in the behavioral sciences (i.e., around .46: Cohen, 1990). Additionally, research has shown that researchers’ intuitions about the statistical power implied by rules-of-thumb sample sizes are inaccurate and overestimate power (Bakker et al., 2016).

In order to assess the efficacy of this more recent call for higher power motivated by the Replication Crisis, on the sample sizes employed in published research, Fraley and colleagues (Fraley et al., 2022; Fraley & Vazire, 2014) quantified the median sample size employed in articles published in nine personality and social psychology journals between 2011 (arguably the start of the Replication Crisis) and 2019. Fraley and colleagues (2022) observed that median sample sizes, and therefore implied statistical power, have indeed increased over the last decade in social and personality psychology research, from very poor (circa .50 in 2011) to acceptable (circa .90 in 2019). In doing so, the Fraley and colleagues (Fraley et al., 2022; Fraley & Vazire, 2014) provided both a relatively simple method to assess the implied power across a body of work and a useful dataset to compare other fields against.

The current study employs this method to provide one of the first examinations of a key determinant of the replicability of research in an area of work relevant to both behaviorism and Contextual Behavioural Science. The stated goal of CBS is “creating a science more adequate to the challenge of the human condition” (Hayes et al., 2012). Efforts to meet this noble goal would be aided by scientific findings that are reliable, reproducible, and replicable (Munafò et al., 2017). This fact was recently recognized by leadership within the CBS community (Task Force on the Strategies and Tactics of Contextual Behavioral Science Research, 2021), which served as motivation for the current work.

The Implicit Relational Assessment Procedure (IRAP)

The Implicit Relational Assessment Procedure (IRAP: Barnes-Holmes et al., 2006) is a reaction-time based task used variously as a measure of implicit attitudes in implicit social cognition research and a measure of the strength of relational responding within Contextual Behavioral Science research (Hughes et al., 2012). One meta-analysis suggested that the IRAP demonstrates relatively high criterion validity compared to other implicit measures such as the Implicit Association Test (Vahey et al., 2015). However, multiple other meta-analyses have also suggested that the IRAP has poor internal consistency (estimates of α from .51 to .60) and unacceptably low test-retest reliability (estimates of r from .13 to .43: Greenwald & Lai, 2020; Hussey & Drake, 2020). This presents somewhat of a conundrum, as the reliability places an upper limit on validity (i.e., through attenuation of observable correlations: Revelle, 2009).

One explanation for these seemingly irreconcilable results is that the IRAP literature may suffer from poor replicability, such as inflated effect sizes and false positive rates. This is not implausible. Although the IRAP grew out of the behaviorist tradition (Barnes-Holmes et al., 2010), IRAP studies typically employ the same research designs and inference methods as Social and Personality psychology (e.g., Null Hypothesis Significance Testing, NHST), and are therefore subject to the same concerns as any research employing this

inference approach. One specific class of statistical methods, multiway Analyses of Variance (ANOVAs), are almost ubiquitous in IRAP research. Research has demonstrated that the modal use of multiway ANOVA inflates false positive rates much higher than the 5% rate implied by the standard alpha level of 0.05 (Cramer et al., 2016). The unavoidable implication is that if the IRAP literature employs a statistical method, which is known to have both inflated false positive rates under modal use and inflated false negative rates under low statistical power, then the published IRAP literature will have inflated rates of false conclusions (i.e., low replicability). At minimum, there is no sound statistical basis by which the IRAP literature could be judged to be a priori immune from such concerns. Rather, the replicability of conclusions in the published IRAP literature must be assessed empirically, via both direct replication studies and assessment of indicators of replicability, such as sample size and statistical power.

It is also worth noting that, given that it is the probability of detecting effects that exist, high statistical power is a desirable property regardless of whether a researcher is employing Null Hypothesis Significance Testing in an inductive manner (Lakens, 2021) or in an inductive manner (e.g., to generate new hypotheses rather than test existing ones). Some IRAP researchers have stated they do the latter (Kavanagh, Matthysen, et al., 2019), although as an aside it should be recognized that this risks representing a form of Hypothesizing After Results Are Known (HARKing: Kerr, 1998), which lowers the replicability of findings (Munafò et al., 2017). Regardless of a researchers' self-identified approach as deductive versus inductive, it should be recognized that a smaller number of high-powered studies generally generates a larger number of true conclusions than a larger number of low-powered studies (LeBel et al., 2017).

The current study therefore represents a first effort toward quantifying two related indicators of replicability in the IRAP literature. I performed a systematic review of published research using the IRAP and then applied Fraley et al.'s (2022; see also Fraley & Vazire, 2014) approach to estimating median sample size over time and the implied statistical power in this literature. As noted in those publications, median sample sizes are more appropriate than other metrics of central tendency (e.g., the mean) due to the strong skew in sample sizes. The median is also highly interpretable as it tells you that half of studies had larger sample sizes than this value and half of studies had smaller sample sizes than this.

Sample sizes in the IRAP literature were then contrasted with sample sizes employed elsewhere. Notionally, a comparison with closely related literatures might seem appropriate, such as studies employing other implicit measures such as the Implicit Association Test (Greenwald et al., 1998), Affect Misattribution Procedure (Payne et al., 2005), or Evaluative Priming Task (Fazio et al., 1995). However, this comparison is

quite extreme: thanks in part to the popularity of the Project Implicit website (implicit.harvard.edu), studies employing other implicit measures often contain thousands of participants (e.g., Hughes et al., 2022), frequently contain tens of thousands (Bar-Anan & Nosek, 2014; Nosek et al., 2007), sometimes contain hundreds of thousands (Hussey et al., 2019), and occasionally even millions of participants (Xu et al., 2014). Of course, the sample sizes employed in the field of implicit social cognition are apparently large not only in comparison to the IRAP but also in comparison to other areas of Social and Personality psychology. As such, it is perhaps more informative to compare sample sizes in the IRAP literature with a more diverse sample as reference, such as the Social and Personality psychology literature as a whole. I therefore made use of the openly available dataset created by Fraley et al. (2022), which covers the Social and Personality psychology literature.

Method

Data was obtained from two separate sources. Research designs and sample sizes within the published IRAP literature were obtained via a systematic review. In order to provide a comparison for this literature, existing data on the research designs and sample sizes reported in articles published in nine Social and Personality Psychology journals was taken from a recent openly-available dataset (Fraley et al., 2022). The data extraction method for the IRAP literature based on the example provided by Fraley et al. (2022).

Systematic review of research designs in the IRAP research (2006-2022)

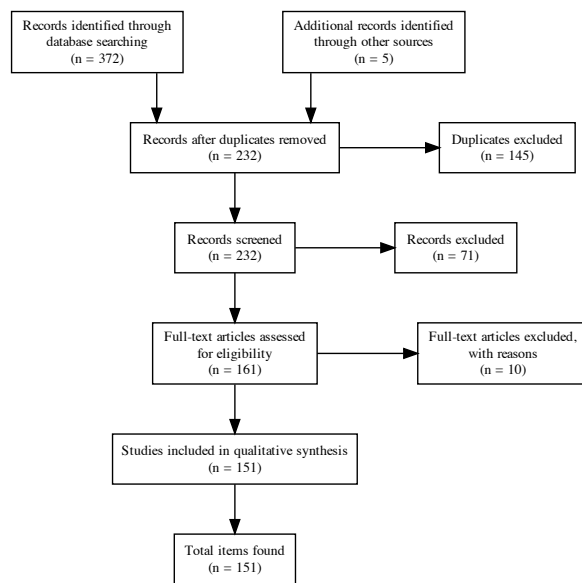
Results from both searches were integrated. Results of each stage of this review are computationally reproducible: bibtex files for all articles at each stage of the search and exclusion process are available in the supplementary materials (osf.io/vpwuy) and can be updated by others or used for other evidence synthesis or meta-science purposes.

Both the Web of Science and psycINFO databases were searched. Boolean search terms for the Web of Science database were "implicit relational assessment procedure" OR "IRAP" in the title, abstract, or keywords. Search constraints were publication date between 2006 and 2022, limited to publications in English. The search was run on 23 December 2018. The systematic review was updated with a second search run on 11 September 2022.

A PRISMA flow chart detailing all exclusions can be found in Figure 1 (Moher et al., 2009). 372 records were obtained from the database searches and 5 from other sources. After duplicates were removed, 232 records remained. The retained records were screened based on their title and abstract. Inclusion criterion was the use of the Implicit Relational Assessment Procedure (IRAP) within the study. Variant procedures such as the Mixed-Trials IRAP (MT-IRAP: Levin et al., 2010) and the Training IRAP (T-IRAP: Kilroe et al., 2014) were excluded. 161 records remained after title and abstract exclusions. The full texts of these articles were then

screened using the same inclusion criterion. Ten articles were excluded based on this full text search. In each case, this was because they did not employ an IRAP (or IRAP variant) at all, or because they employed an IRAP variant such as a Training IRAP or Mixed-Trials IRAP. A list of these exclusions and their individual reasons is available in the supplementary materials. After all exclusions, 151 published articles and book chapters using the IRAP were found that met the inclusion criteria.

Figure 1. PRISMA flow chart for systematic review



The full text for each record was then inspected in order to extract the following information for each study described: the sample size after exclusions (N); study design (between, within, or mixed); the number of between-subjects conditions; and whether the study reported employing Null Hypothesis Significance Testing (NHST). The sample size after exclusions was extracted rather than the sample prior to exclusions given the IRAP's established high attrition rate (Hussey et al., 2015). Note that comparisons among multiple IRAP trial-types was excluded from consideration when labelling a given study as including a within-subjects element, given that this feature is so common in the literature. Where a study employed multiple designs (e.g., both correlating the IRAP with a criterion variable and examining the pattern of IRAP effects between groups) it was labelled "mixed". As such, "mixed" refers not only to mixed within-between research designs but also articles that report both within and between designs. This was suitable for the current analytic purposes, which required excluding the purely within-subject studies from the analyses in order to estimate statistical power correctly (i.e., using those studies employing at least one between-subjects analysis).

Review of research practices in Social and Personality Psychology journals (2011-2019)

Fraley et al. (2022) recently reviewed the sample sizes employed in nine Social and Personality Psychology journals (European Journal of Social Psychology, European Journal of Personality, Journal of Experimental Social Psychology, Journal of Personality, Journal of Personality and Social Psychology, Journal of Research in Personality, Personality and Social Psychology Bulletin, Psychological Science, and Social and Personality Psychology Science). The authors extracted data from a random 20% of the empirical studies published in each journal in each year between 2011 and 2019. According to the authors, their chosen start date corresponded to the beginning of the Replication Crisis in psychology, which many would place at the publication of impactful papers by Bem (2011) and Simmons et al. (2011). As in Fraley et al. (2022), (a) only data from studies that employed between-subjects comparisons were employed for the below analyses; and (b) only studies in Social and Personality psychology were included. Studies published in Psychological Science, which is a general psychology journal, were individually screened by Fraley et al. (2022) for their relevance to Social or Personality psychology and excluded appropriately. Their openly available dataset was obtained from their supplementary materials (i.e., osf.io/rvbxp). The analytic dataset included sample sizes from 3047 studies (range 113 to 631 studies per journal).

Results

Prevalence of Null Hypothesis Significance Testing in the IRAP literature

Given that the IRAP emerged from the behavioral tradition (Barnes-Holmes et al., 2010), I considered it possible that some IRAP studies may employ inference methods other than Null Hypothesis Significance Testing (NHST), including Single Case Experimental Design methods. Such studies would be both likely to employ smaller sample sizes and would not be susceptible to issues of statistical power in quite the same way as those which explicitly employed NHST. As such, prior to applying any critique that was relevant only to studies employing NHST, I first began by quantifying the proportion of IRAP publications that actually employed NHST.

One publication did not report the sample size (Cullen & Barnes-Holmes, 2008). The remaining 150 publications contained 188 studies. Just 3 studies in two articles (1.6%) did not employ NHST (i.e., Jackson et al., 2016; Rafacz et al., 2019). The overwhelming majority of published IRAP studies have employed NHST (185 studies, 97.9%). As such, the constraints of inference via NHST necessarily apply to these studies.

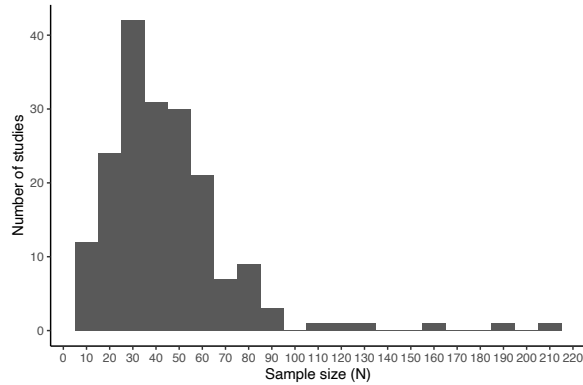
Sample size in the IRAP literature

Distribution of sample sizes

In the 185 studies that both employed NHST and reported sample sizes, a total of 8384 participants were reported. Sample sizes ranged from 9 to 210 participants,

Median = 41, Median Absolute Deviation (MAD) = 17.8. A histogram of the distribution of sample sizes in IRAP research can be found in Figure 1.

Figure 1. Histogram of the distribution of sample sizes in IRAP studies



Change in sample size per study over time

Change in sample sizes over time was quantified by calculating the median sample size for each year. In order to illustrate the change in sample sizes used in all IRAP studies over time, median sample size per study per year using all studies was calculated (see Figure 2, green line). In this and all subsequent figures, the straight line represents the fitted Ordinary Least Squares linear regression line (discussed later) and the shaded region around it represents its 95% Confidence Interval. As can be seen in the plot, median sample sizes in IRAP studies are small (range 12 to 64). Notably, given that these are medians, this also implies that half of studies in each year employ samples that are even smaller than this. Data from all plots are available in table format in the supplementary materials (osf.io/4v3qa).

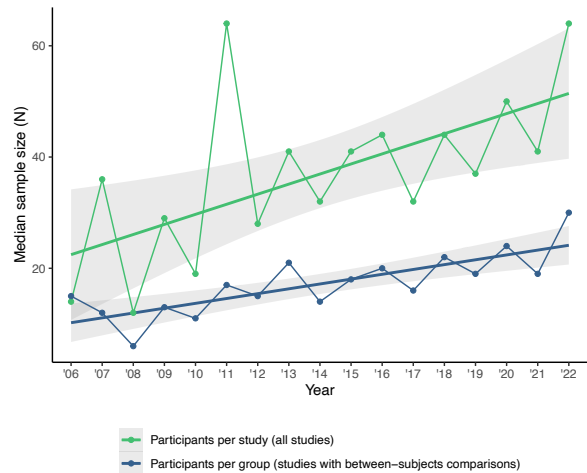
In order to quantify change in an accessible manner, an Ordinary Least Squares linear regression was fit to the data with median sample size as the dependent variable and year as the independent variable. Year was rescored so that 2006 was the intercept. Results demonstrated that estimated median sample size per study was increasing from an estimated 22.5, 95% CI [10.7, 34.2] in 2006 (the model intercept) by an average of 1.8, 95% CI [0.6, 3.1], $p = .008$ participants per year (see Figure 2, green line).

Change in sample size per group over time

While the previous quantification benefits from including data from all studies and therefore providing an overview of the literature, it does not necessarily compare like with like over time in a way that facilitates understanding statistical power. For example, imagine two studies: the first has a sample size of 100 in two between-subject conditions, the second has a sample size of 150 in three between-subject conditions. The studies have different sample sizes, but this does not translate to them having higher statistical power for their pairwise

group comparisons: both have an average of 50 participants per group. In order to compare like with like, it is useful to also plot median sample per group (aka cell within the factorial design). Median sample size per experimental group per year was therefore calculated by dividing the study sample size by the number of between-subjects groups employed within each study. Similarly, in order to compare like with like, only studies employing between groups comparisons were included (69.5% of all studies). This rationale follows that employed by Fraley et al. (2022). Figure 2 therefore also plots median sample size per study per year using all studies was calculated (see Figure 2, blue line).

Figure 2. Median sample size per year in IRAP studies



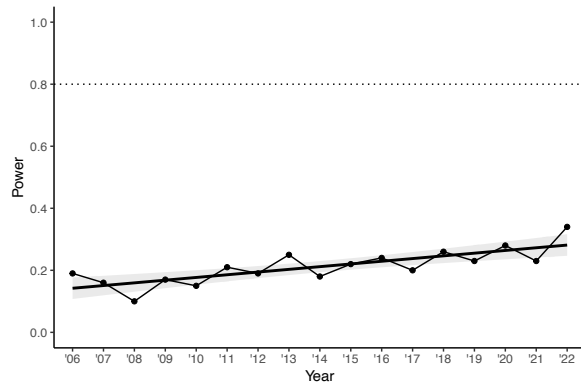
A similar regression was fitted this time using median sample sizes per group as the dependent variable. Results demonstrated that estimated median sample size per group was increasing from an estimated 10.2, 95% CI [6.8, 13.7] in 2006 (the model intercept) by an average of 0.9, 95% CI [0.5, 1.2], $p < .001$ participants per year (see Figure 2, blue line). Caveats about robustness notwithstanding, because this analysis compares like with like better than the previous one, these results likely represent a more appropriate estimation of the change in sample sizes over time with regard to implications for statistical power.

Statistical power in the IRAP literature

I then quantified the median statistical power that these median sample sizes imply. It is important to recall that statistical power is a function of multiple variables other than sample size, and power and sample size should not be treated as synonymous. Power is a function of (1) a specific type of test, (2) its alpha level, (3) whether one-tailed or two-tailed hypotheses are employed, (4) the sample size estimate, and (5) the effect size of interest. Choices must be made for each of these in order to estimate power. As in Fraley et al. (2022), I therefore (1) limited my consideration to specific analyses (i.e., independent t -tests or Pearson's r correlations, using equivalent effect sizes for each); (2)

employed the standard alpha level of .05; (3) employed modal two-tailed comparisons; (4) estimated the median sample size from the literature that used broadly consistent designs (i.e., median N estimated from studies that reported at least one between-subjects comparison, excluding exclusively within-sample designs); and (5) estimated the ability to detect an effect size of Cohen's $d = .408$. This effect size is equivalent to a Pearson's $r = .20$ (as used in as used in Fraley et al., 2022), which has been shown in multiple meta-analyses to be approximately the average size effect found across the psychology research literature (Gignac & Szodorai, 2016; Hemphill, 2003; Richard et al., 2003).

Figure 3. The statistical power to detect the average published effect size (Cohen's $d = 0.408$ or Pearson's $r = 0.20$) implied by median sample size per group per year in IRAP studies



Implied statistical was calculated using the above parameters for each year using the R package pwr (Champely, 2016). Results can be found in Figure 3. The dotted line represents Cohen's (1988) commonly accepted guideline for a minimum of at least .80 power. As can be seen in the plot, implied statistical power to detect an average effect size in the IRAP literature is very low (range .10 to .34).

In order to illustrate the magnitude of change in power over time, power and median sample size were entered into a regression as the dependent variable, otherwise similar to the previous analyses. Results demonstrated that the implied statistical power to detect the average published effect size (Cohen's $d = 0.408$, equivalent to Pearson's $r = 0.20$) was increasing from an estimated .142, 95% CI [.108, .177] in 2006 (the model intercept) by an average of .009, 95% CI [.005, .012], $p < .001$ participants per year. This estimate was used to calculate how long it would take to achieve Cohen's (1988) recommendation of power of at least .80. If this linear rate of growth continued, the median IRAP sample size would take another 58 years to reach this commonly accepted minimum for statistical power (i.e., in 2080). Note that this is not a prediction that the rate of growth will be linear or stable, but a prediction based

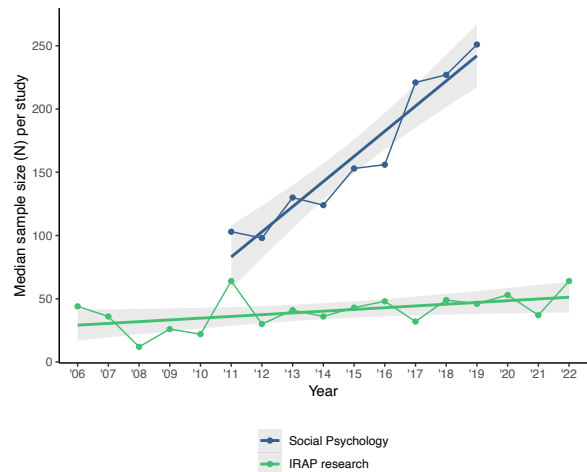
on these assumptions, in a world where IRAP researchers' behavior stays on their current trajectory.

Comparing the IRAP literature with Social and Personality Psychology

The analyses reported in the previous section demonstrate that median sample sizes and implied statistical power in the IRAP literature are low in absolute terms. It is useful to supplement this with a relative comparison, i.e., to research in other areas, using the dataset provided by Fraley et al. (2022). Whereas Fraley et al. (2022) calculated median sample size by journal, I calculate a single overall median for Social and Personality and psychology in order to make a simple comparison between these two literatures.

However, Fraley et al. (2022) did not extract the number of between-subjects groups employed in each study, only the design (between, within, or mixed within-between) and sample size. The most direct and informative comparison possible with the IRAP literature is therefore the comparison of median sample sizes by study in studies that employed between-subjects comparisons (i.e., where the analyses in the previous section compared medians by group rather than by study). Medians and power will therefore differ between the analyses reported in these analyses and those reported in the previous section. Analyses in the previous section represent more appropriate absolute estimates, whereas those reported here are more useful for comparisons.

Figure 4. Median sample size per year in IRAP studies compared to Social and Personality Psychology studies



Comparing median sample sizes

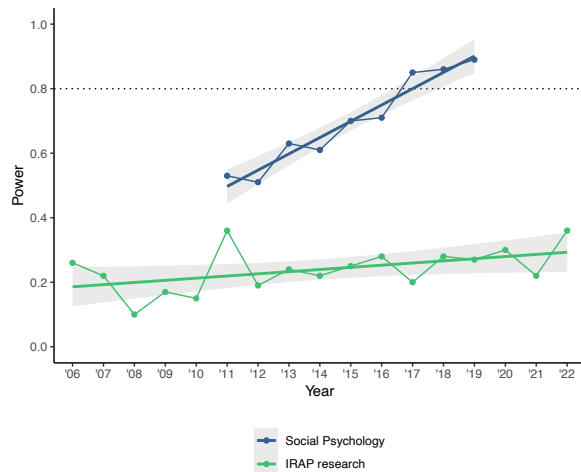
Figure 4 illustrates the median sample sizes per study per year for IRAP studies (green line) compared to the Social and Psychology literature (blue line). A regression was fitted to the data, with median sample size as the dependent variable; and year, literature (IRAP literature vs. Social and Personality psychology literature), and their interaction as independent variables. The estimate of the interaction effect was used

to test the hypothesis that the change in median sample size over time was larger in Social and Personality psychology studies than IRAP studies. Results demonstrated that this difference was statistically significant, substantive in size, and in the predicted direction, $B = 18.5$, 95% CI [14.5, 22.5], $p < .001$.

Comparing statistical power

The statistical power implied by each median sample size was then calculated using the same manner as previously. See Figure 5, in which the dotted line represents Cohen's (1988) commonly accepted guideline for a minimum of at least .80 power. Power estimates were then entered into a regression as the dependent variable. The independent variables were identical the previous regression model. The estimate of the interaction effect was used to test the hypothesis that the change in implied statistical power to detect the average published effect size (Cohen's $d = 0.408$, equivalent to Pearson's $r = 0.20$) over time was larger in Social and Personality psychology studies than IRAP studies. Results demonstrated that this difference was statistically significant, substantive in size, and in the predicted direction, $B = .04$, 95% CI [.03, .06], $p < .001$.

Figure 5. The statistical power to detect the average published effect size (Cohen's $d = 0.408$ or Pearson's $r = 0.20$) implied by median sample size per study per year in IRAP studies compared to Social and Personality Psychology studies



Discussion

Results demonstrated the sample sizes employed in IRAP literature have been problematically small in both absolute terms and relative to the sample sizes employed in Social and Personality psychology studies. The statistical power to detect the average effect size in published psychology research (i.e., Cohen's $d = 0.408$, equivalent to Pearson's $r = .20$; Gignac & Szodorai, 2016; Hemphill, 2003; Richard et al., 2003) implied by the median sample sizes in IRAP research are also problematically low in both absolute terms and relative to that in the Social and Personality psychology

literature. Implied statistical power was $< .35$ in all years, where Cohen (1988) recommends a minimum power of .80.

Although the sample sizes employed in IRAP studies (and therefore implied power) are increasing detectably over time, the rate of this increase is too low to make meaningful progress. Results suggest that if the current rate of linear increase in median sample sizes continued it would take 58 years for just half of IRAP studies to meet Cohen's (1988) recommendation of power of a minimum of least .80 (i.e., in 2080).

When compared with the sample sizes employed in 3047 studies published across nine Social and Personality psychology journals (Fraley et al., 2022), results demonstrated that median samples sizes (and therefore implied statistical power) increased at a much greater rate in Social and Personality psychology between 2011 and 2019 than they did in IRAP studies between 2006 and 2022. Furthermore, median sample sizes and their implied statistical power were lower in the IRAP literature in all years than they were at the beginning of the Replication Crisis in Social and Personality psychology in 2011, and indeed in all subsequent years (see Figures 4 and 5).

The necessary implications of this low power must be appreciated: they imply that of all effects of average size in the population that have been studied in IRAP publications, those effects that truly exist in the population were not detected in nearly two thirds of cases. Even for those researchers who self-identify as employing NHST in an inductive manner (e.g., Kavanagh, Matthyssen, et al., 2019) this would imply most opportunities to induce hypotheses from data are missed because there was insufficient power to generate significance results. Simulation studies such as those by Bakker and colleagues (2012) and LeBel and colleagues (2017) demonstrate that a smaller number of better powered studies produces a larger number of true inferences than a larger number of less well powered studies. As such, even researchers with very limited resources available to them would be better to allocate those resources to larger studies.

Recommendations for power analyses and sample sizes

Readers might reasonably seek concrete recommendations for sample sizes in future IRAP studies. Unfortunately, my answer may be unsatisfying: (1) it depends, and (2) it should probably be much larger than you think. This position is drawn from a few sources. First, the authors of the seminal article "False Positive Psychology" paper (2011) have since stated that one of their biggest regrets in that paper was to specify a minimum sample size, due to the subsequent misuse of that recommendation (Simmons et al., 2018). It's worth noting that similar misuses of sample size recommendations are already visible within the IRAP literature: Vahey and colleagues (2015) reported an analysis of the IRAP's clinical criterion validity and the results of multiple power analyses based on their effect size estimate. Citations of Vahey et al. (2015) often

inappropriately or inaccurately cite these recommendations. For example, many papers make reference to the sample size recommendation reported in Vahey et al.'s (2015) abstract (i.e., " $N = 29$ to 37 ") even when the authors are employing a completely different analyses (e.g., other than a one-tailed Pearson's r correlation with α -level = .05) and/or are conducting research outside of the clinical domain to which Vahey et al. (2015) limited the scope of their meta-analysis (e.g., Farrell et al., 2015; Kavanagh et al., 2016; Kavanagh, Roelandt, et al., 2019; Leech & Barnes-Holmes, 2020; Maloney & Barnes-Holmes, 2016).

Second, research has demonstrated that researchers' intuitions about the relationship between statistical power and sample size are inaccurate and tend to greatly over-estimate power (Bakker et al., 2016). Deeper engagement with sample size choices and their power implications is therefore warranted.

In light of the above, it seems important to not provide sample size recommendations that risk being cited or followed unthinkingly, absent of context or specifics. Instead, I encourage readers to think more deeply about their inference method, engage with the concept and calculation of statistical power, and plan their studies accordingly. In general, power analyses should be conducted and reported in a reproducible manner, for example for example using the `pwr` R package (Champely, 2016) or `Superpower` (Caldwell et al., 2022). For a beginner introduction to statistical power using interactive visualizations, see Magnusson (2023). For a seminal book-length treatment see Cohen (1988).

Tests of interaction effects are often reported in the IRAP literature, typically via the interaction term in multiway ANOVAs. Determining statistical power for interaction terms is more complex than implied by some power analysis software such as `G*Power` (Faul et al., 2007), and I recommend that researchers should base power analyses on specific forms of expected or plausible interactions (e.g., reversed, fully attenuated, partially attenuated) and their post hoc tests rather than the interaction term in an ANOVA alone (see Caldwell et al., 2022; Sommet et al., 2022).

Sample size determination also involves additional considerations beyond power analysis, such as availability of resources and desired precision (Lakens, 2022). Researchers should consider that sample sizes employed in power analyses do not have to be based on as-yet unknown estimates of the effect size they are studying, but can instead be based on the researchers' Smallest Effect Size of Interest (SESOI; Lakens, Scheel, et al., 2018). Previous work has also pointed out ways in which standard power analyses may still under-power studies due to between-study heterogeneity. This may require that sample sizes be increased further. For discussion of this issue as well as materials for performing power analyses that can account for this see McShane and Böckenholt (2014).

Of course, power is not the only factor that influences the quality of inferences when using NHST. Exploratory multiway ANOVAs are commonly reported in IRAP publications, and yet corrections for multiple testing (i.e., to control the family-wise error rate) are rarely applied. Cramer and colleagues (2016) demonstrated that this factor alone gives rise to false positive rates that are greatly inflated beyond the 5% implied by an α -level of 0.05 (e.g., >14%). Exactly how high false positive rates are inflated for the specific types of multiway ANOVAs employed in IRAP research (e.g., 4 X 2 mixed within-between repeated measures ANOVAs) remains unclear. Future research may wish to examine this in simulation studies.

Many other factors influence the replicability of findings, providing many opportunities for researchers to improve the strength of evidence provided by their studies (Nosek et al., 2018). Researchers should therefore also give serious consideration to preregistering their sample size planning justifications, their chosen sample size, stopping rule, precise analysis plan, and other elements of their research, such as their chosen α -level (Lakens, Adolfs, et al., 2018).

Limitations

Choice of effect size

One limitation of the current study is the choice of the effect size for which power was calculated for (i.e., Pearson's $r = .20$, equivalent to Cohen's $d = .408$). This value was selected in order to be able to draw direct comparisons with Fraley et al. (2022) and therefore the literature on Social and Personality psychology. Additionally, this estimate was derived from multiple large scale meta-science studies estimating the average effect size reported in psychology research across thousands of papers (Gignac & Szodorai, 2016; Hemphill, 2003; Richard et al., 2003). No such estimates exist for the IRAP literature.

One meta-analysis of the IRAP's criterion validity does exist (Vahey et al., 2015), but that study involved a different estimand to the current work (i.e., it provided an answer to a different question). Whereas the current analyses require an estimate of all average observed effect sizes, Vahey et al. (2015) included just 15 of 46 publications they found, and 56 effect sizes of the at least 308 effect sizes reported in those articles. These publications and effect sizes were not sampled randomly but by applying inclusion criteria related to clinical relevance, making their estimate unsuitable for the current purposes.

Potential for systematic differences in effect sizes between literatures

It is important to consider the possibility that the effect sizes observed within the IRAP literature are simply much larger than those observed in other areas of psychology. This would undermine the comparisons between the implied power in the IRAP literature versus the Social and Personality Psychology literature which are based on an assumption of similar average effect sizes. However, this would require that the IRAP itself is

unique or distinct in some way that allows it to capture larger than average effect sizes. Given that the IRAP is used to study a diverse range of topics covering social psychology (e.g., race and gender: De Schryver et al., 2018; Hughes et al., 2016), clinical psychology (e.g., depression, suicidality, eating disorders, and OCD: Hussey et al., 2016; Hussey & Barnes-Holmes, 2012; Nicholson & Barnes-Holmes, 2012; Parling et al., 2012), and behaviorism (e.g., within Relational Frame Theory: Finn et al., 2016; Pidgeon et al., 2021), the common link across the IRAP literature is therefore not the domain in which the task is employed, but the use of the task itself. While it is quite feasible that effect sizes differ in one domain relative to another (e.g., effect sizes in persuasion research might simply be larger than in perception research, or vice versa), this is not the case when a range of domains are being considered.

It is relatively easier to estimate the probability that larger effect sizes will be observed using one task relative to others: average observable effect sizes are limited by the reliability of the task being used to capture them (i.e., via attenuation: Revelle, 2009). The IRAP's reliability has been shown to be less than acceptable according to common recommendations (e.g., $\alpha = .60$ and test-retest $r = .43$ according to one meta-analysis: Greenwald & Lai, 2020; reliability was found to be substantially lower in a different analysis: Hussey & Drake, 2020a; recommendation for $\alpha > .70$: Nunnally & Bernstein, 1994). Measures in Social and Personality psychology have generally been shown to possess higher reliability than this in reliability-generalization meta-analyses (Greco et al., 2018). It is mathematically implausible that a less reliable than average task can consistently capture larger than average effect sizes. As such, it is unlikely that average effect sizes in the IRAP literature are larger than those in other literatures (although the reverse is plausibly the case).

Generalizability

The limitations of the dataset generated by Fraley et al. (2022) covering the Social and Personality psychology literature are discussed in their original article and will be reiterated here. Those authors elected to code articles from a subset of the more prestigious Social and Personality psychology journals, and there is potential that their estimates are not perfectly representative of articles published in other journals in that field. Only increasingly larger scale assessments of literature can resolve this. There are already signs of progress here: Fraley et al. (2022) have already updated their dataset once (see Fraley & Vazire, 2014) and state that they will continue to do so again in the future.

The current research represents an effort to extend this form of assessment beyond Social and Personality psychology. It is unclear whether the present results for the IRAP literature would generalize to the broader behavioral literature. Given recent calls for scrutiny of the replicability of behavioral research (e.g., Hantula, 2019; Task Force on the Strategies and Tactics of Contextual Behavioral Science Research, 2021), future

research should examine median sample sizes in studies employing NHST in the behavioral literature (e.g., journals such as Journal of Contextual Behavioral Science, The Psychological Record, and Perspectives of Behavioral Science).

Conclusion

Given that statistical power across a literature is a key determinant of the replicability of the findings in that literature, these results paint a worrying picture for the replicability of IRAP research. These concerns add to concerns vocalized elsewhere about the IRAP's reliability (Hussey, 2020; Hussey & Drake, 2020a), a method factor that confounds several common analyses of IRAP data (Hussey & Drake, 2020b), and the fact that most IRAP studies come from a very narrow range of individuals and labs, potentially impacting the replicability and generalizability of claims (Hussey, 2022). Researchers should therefore interpret the results and conclusions of published IRAP research with some caution, and be cautious in choosing to employ the IRAP in their own work. In line with a recent statement by the Association for Contextual Behavioral Science explicitly embracing the need for replication studies (Task Force on the Strategies and Tactics of Contextual Behavioral Science Research, 2021), direct assessments of the reproducibility and replicability of the published IRAP literature is likely warranted.

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Statements and Declarations

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Conflict of Interest

The author declares that he has no relevant financial or non-financial interests to disclose.

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Availability of data, code and materials

All data, code and materials are available at osf.io/vpwuy. A supplementary materials document is available at osf.io/4v3qa.

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