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Individual Participant Data (IPD) Meta-Analysis of Single-Case Experimental Design Data Including Moderators: Empirical Validation

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Acknowledgement

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1. Moeyaert, M., Yang, P., & Xue, Y. (2023). Individual Participant Data Meta-Analysis Including Moderators: Empirical Validation. *The Journal of Experimental Education*, 1-18. https://doi.org/10.1080/00220973.2023.2208062
2. Moeyaert, M. (September, 2022). *Using multilevel modeling for meta-analyzing single-case design research*. Seminar Systematic Reviews and Meta-Analysis Methodology, The AERA SIG SRMA and MATI.
3. Xue, Y., Moeyaert, M., & Yang, P. (April, 2023). *Individual participant data (IPD) meta-analysis including moderators: Empirical validation*. Poster Presentation at the 3rd International Online N=1 Symposium "Small is Beautiful {Once More }". https://ppw.kuleuven.be/ogp/smallisbeautifuloncemore2023

- The presentation is based on the above paper and the presentations.
- The project was initiated and supervised by **Dr. Mariola Moeyaert** and received invaluable input from **Dr. Panpan Yang**.

Outline

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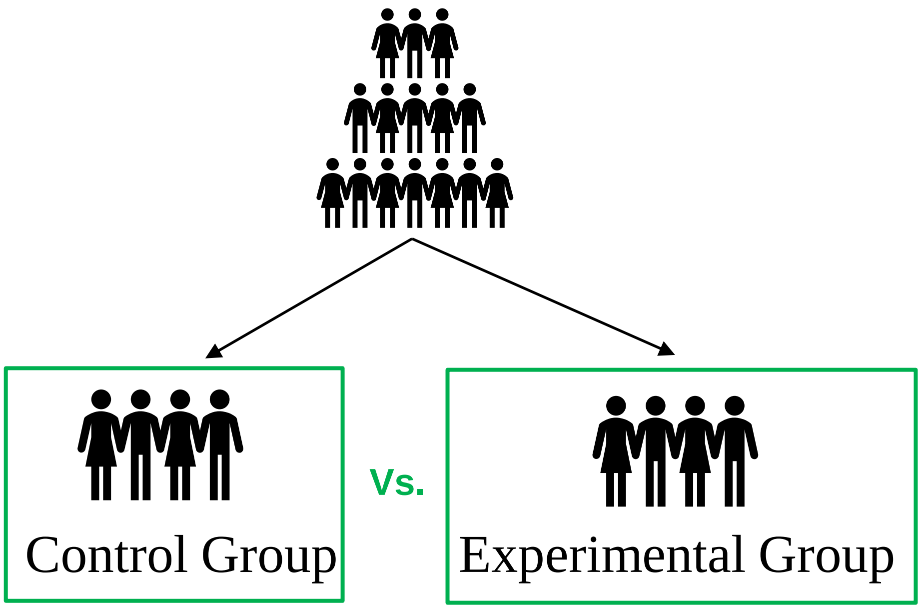
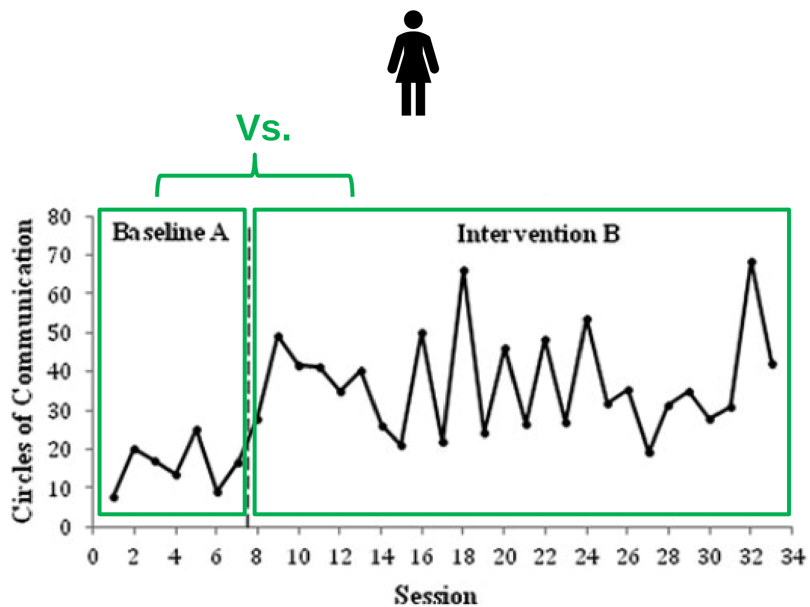
1. Conceptual Framework
   1.1 Single-Case Experimental Research
   1.2 Two-Stage IPD Meta-Analysis
2. Empirical Validation: Monte Carlo Simulation
3. Conclusion and Future research
4. Questions

1. Conceptual Framework

Single-case experimental designs (SCED) is a scientifically rigorous alternative to randomized controlled trial (RCT) designs.



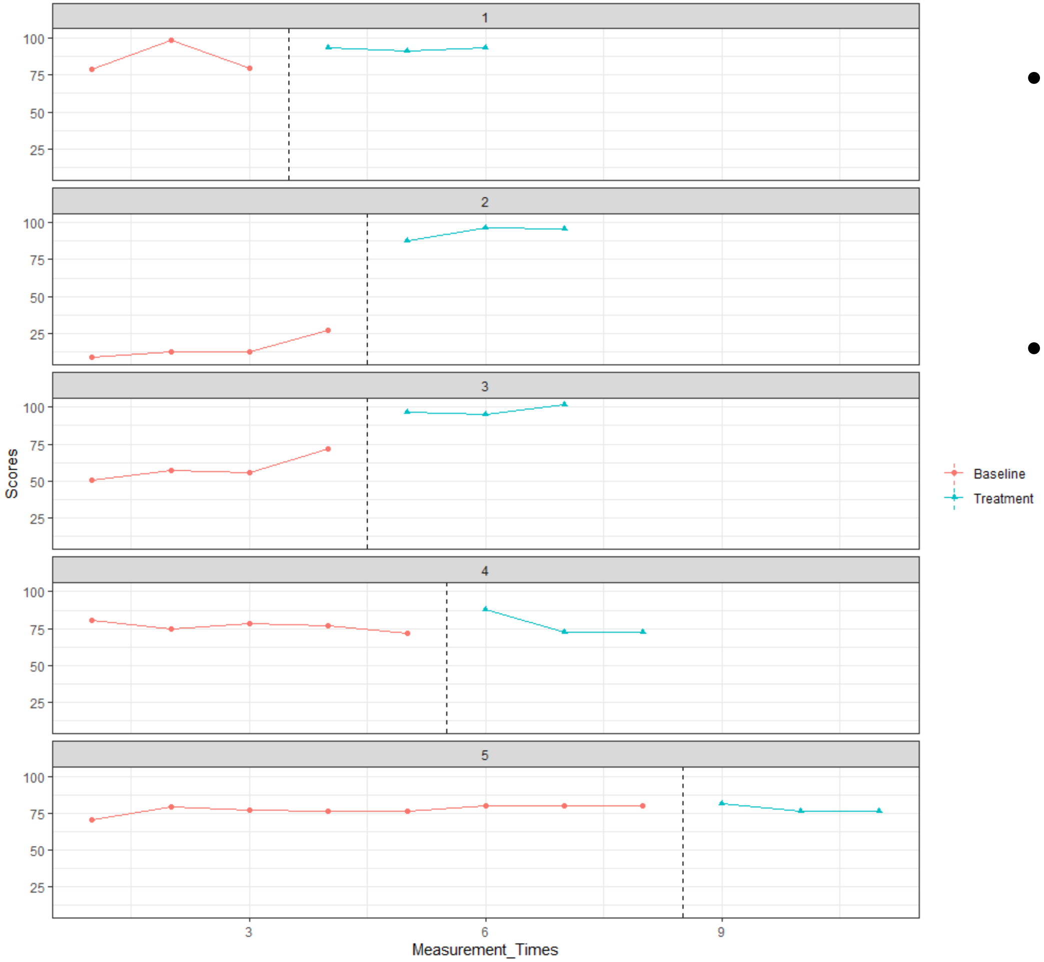
An example of RCT Design



An example of Single-Case Experimental Design (An AB design for one participant) (Lobo et al., 2017)

1. Conceptual Framework

The are a variety of SCEDs that can be considered as extensions of the basic AB design, such as the multiple-baseline design (MBD).

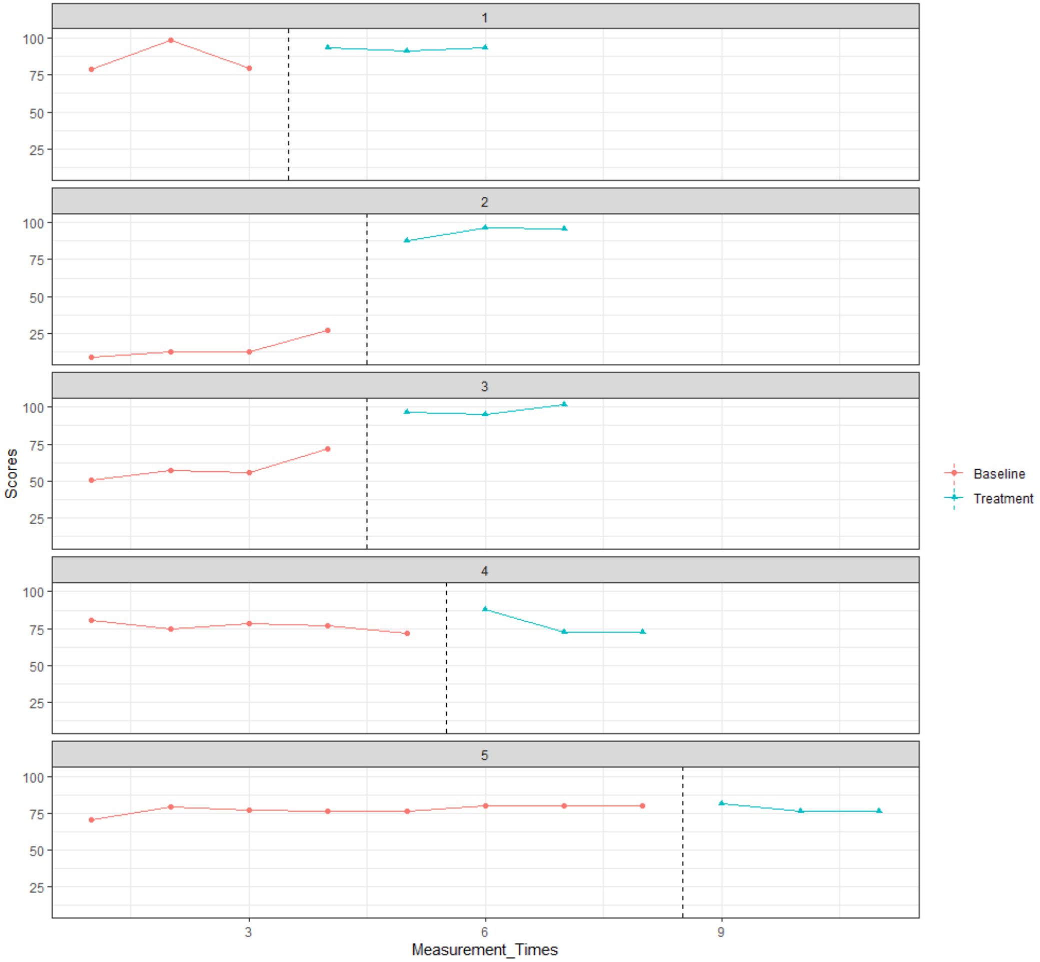


- MBD is one of the most used SCED in practice (Shadish & Sullivan, 2011).

- Using motivational general-mastery imagery to improve the self-efficacy of youth squash players (Munroe-Chandler et al., 2014).
    - **Participants**: 5 youth squash athletes
    - **Outcome**: Squash-specific self-efficacy
    - **Intervention**: Motivational general-mastery imagery intervention

1. Conceptual Framework
Single-case experimental designs

Multiple-Baseline Design (MBD)



- Suitable for conditions when a return-to-baseline performance is not feasible.
- The start of the intervention are staggered across participants.
- Multiple participants are included as within-study replications to provide multiple demonstrations of intervention effectiveness.

1. Conceptual Framework
Meta-Analysis of SCED Data

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- Using meta-analysis for SCED data, several key questions can be answered.

Purposes of Using Meta-Analysis	Research Questions to be Answered
Summarizing magnitude of intervention effects.	What is the overall average treatment effect across studies?
Investigating intervention heterogeneity.	Do the intervention effects vary across participants and studies?
Identifying moderators to explain intervention heterogeneity.	What participant factors and study factors are related to various intervention effects?

1. Conceptual Framework
IPD Meta-Analysis: What?

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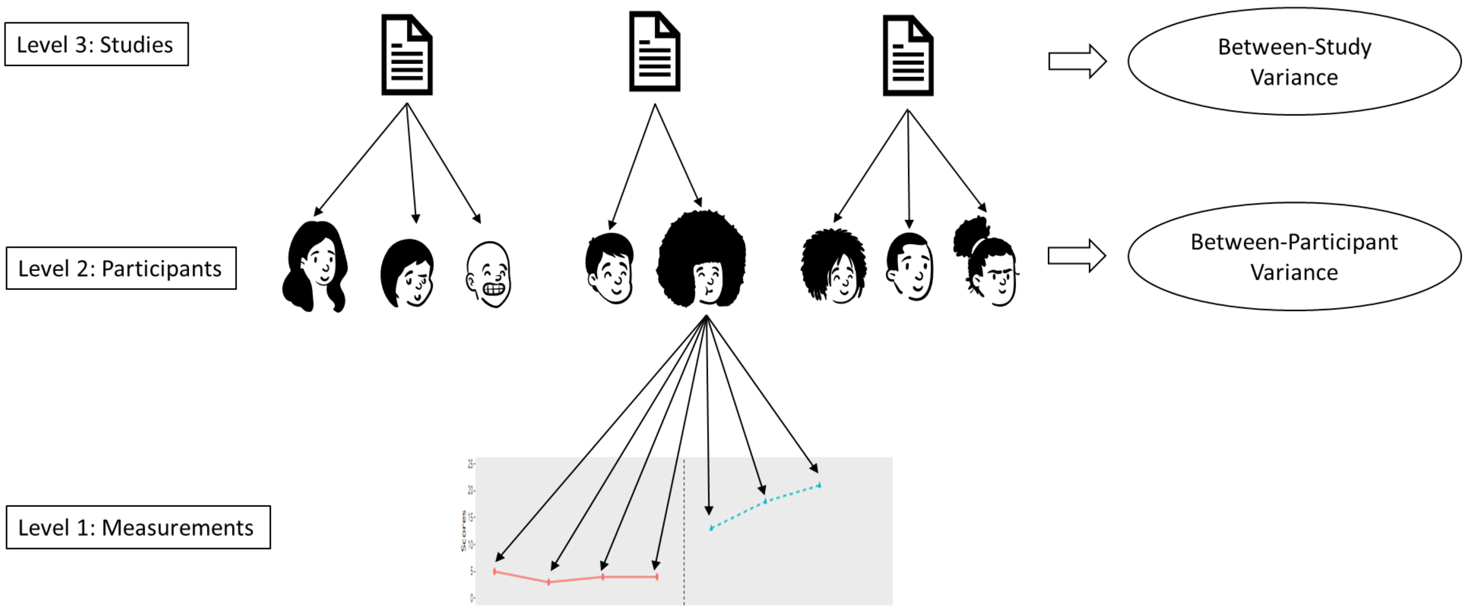
- Individual Patient/Participant Data (IPD) meta-analysis is also called raw SCD data meta-analysis (Declercq et al. 2022, Moeyaert & Fingerhut, 2022).
- Raw data from multiple participants and studies are extracted and synthesized.
- Three-level structure:



1. Conceptual Framework

IPD Meta-Analysis: Why?

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Aggregated data meta-analysis	Individual Participant Data meta-analysis
Basic analytic unit: aggregated intervention effectiveness per study.	Basic analytic unit: a measurement score for each participant at each timepoint in each study (hierarchical structure).
Between-participant variance in intervention effectiveness cannot be estimated.	Between-participant and between-study variance can be estimated.
No participant-specific moderators can be included.	Moderators at both the participant and study level can be investigated to explain intervention heterogeneity.
Easy to be understood, applied, and interpreted.	Demands some experience with statistical modeling.

1. Conceptual Framework

IPD Meta-Analysis: Statistical Models

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Statistical Model - IPD Meta-Analysis Approaches

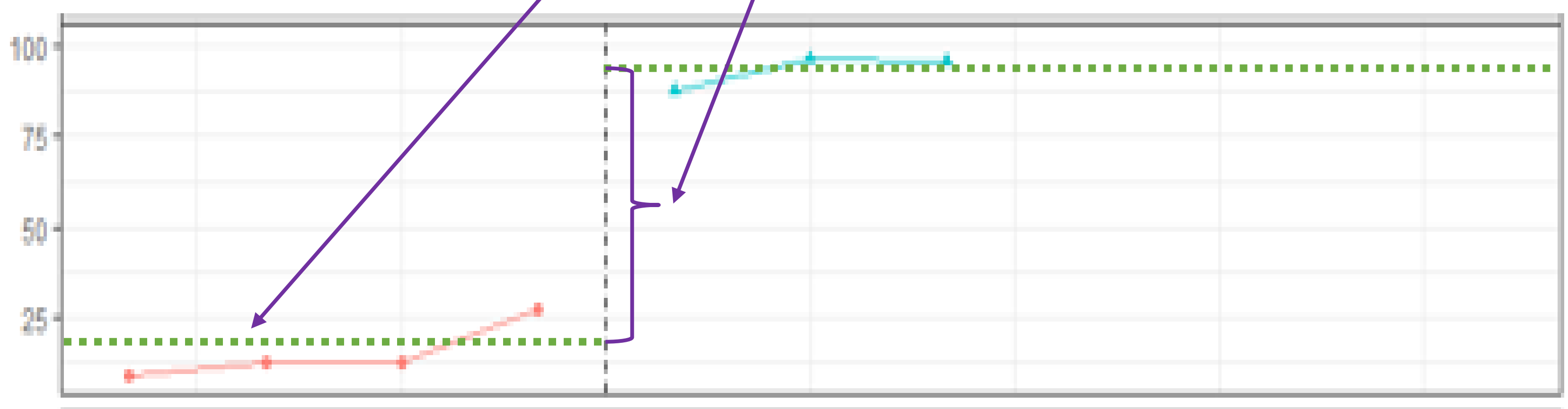
A three-level modeling for IPD meta-analysis of SCED data Without Moderators

Level 1	$Y_{ijk} = \beta_{0jk} + \beta_{1jk}D_{ijk} + e_{ijk}$ with $e_{ijk} \sim N(0, \sigma_e^2)$

Assuming the data below comes from **participant 3** (*j* = 3) from **Study 2** (*k* = 2):

$$Y_{i32} = \boxed{\beta_{032}} + \boxed{\beta_{132}} D_{132} + e_{i32}$$

$D_{132} = 0$ when the data point comes from the baseline phase, and $D_{132} = 1$ when the data point comes from the intervention phase.



1. Conceptual Framework
IPD Meta-Analysis: Statistical Models

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Statistical Model - IPD Meta-Analysis Approaches

A three-level modeling for IPD meta-analysis of SCED dada Without Moderators

Level 1	$Y_{ijk} = \beta_{0jk} + \beta_{1jk} D_{ijk} + e_{ijk}$ with $e_{ijk} \sim N(0, \sigma_e^2)$
Level 2	$\beta_{0jk} = \theta_{00k} + u_{0jk}; \beta_{1jk} = \theta_{10k} + u_{1jk}$ with $(u_{0jk}\ u_{1jk}) \sim \text{MVN}\ [\binom{0}{0}, \begin{pmatrix} \sigma_{u_0}^2 & \\ \sigma_{u_{01}} & \sigma_{u_1}^2 \end{pmatrix}]$
Level 3	$\theta_{00k} = \gamma_{000} + v_{00k}; \theta_{10k} = \gamma_{100} + v_{10k}$ with $(v_{00k}\ v_{10k}) \sim \text{MVN}\ [\binom{0}{0}, \begin{pmatrix} \sigma_{v_0}^2 & \\ \sigma_{v_{01}} & \sigma_{v_1}^2 \end{pmatrix}]$
Combined	$Y_{ijk} = \gamma_{000} + v_{00k} + u_{0jk} + (\gamma_{100} + v_{10k} + u_{1jk}) D_{ijk} + e_{ijk}$ with $e_{ijk} \sim N(0, \sigma_e^2)$, $[u_{0jk}\ u_{1jk}] \sim \text{MVN}\ [\binom{0}{0}, \begin{pmatrix} \sigma_{u_0}^2 & \\ \sigma_{u_{01}} & \sigma_{u_1}^2 \end{pmatrix}]$, and $[v_{00k}\ v_{10k}] \sim \text{MVN}\ [\binom{0}{0}, \begin{pmatrix} \sigma_{v_0}^2 & \\ \sigma_{v_{01}} & \sigma_{v_1}^2 \end{pmatrix}]$

1. Conceptual Framework

IPD Meta-Analysis: Statistical Models

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Statistical Model - IPD Meta-Analysis approaches

One-stage IPD meta-analysis

$$y_{ijk} = \beta_{0jk} + \beta_{1jk}D_{ijk} + e_{ijk} \; with \; e_{ijk} \sim N(0, \sigma_e^2)$$

$$\begin{cases} \beta_{0jk} = \gamma_{000} + u_{0jk} + v_{00k} \\ \beta_{1jk} = \gamma_{100} + u_{1jk} + v_{10k} \end{cases}$$

$$\begin{pmatrix} u_{0jk} \\ u_{1jk} \end{pmatrix} \sim MVN\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_{u_0}^2 & \\ \sigma_{u_{01}} & \sigma_{u_1}^2 \end{pmatrix}\right]$$

$$\begin{pmatrix} v_{0jk} \\ v_{1jk} \end{pmatrix} \sim MVN\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_{v_0}^2 & \\ \sigma_{v_{01}} & \sigma_{v_1}^2 \end{pmatrix}\right]$$

Two-stage IPD meta-analysis

Stage 1

$$y_{ijk} = \beta_{0jk} + \beta_{1jk}D_{ijk} + e_{ijk} \; with \; e_{ijk} \sim N(0, \sigma_e^2)$$

$$b_{1jk} = \beta_{1jk} + r_{jk}$$

Stage 2

$$\beta_{1jk} = \gamma_{100} + u_{1jk} + v_{10k}$$

$$u_{1jk} \sim N\left(0, \sigma_{u_{1jk}}^2\right)$$

$$v_{10k} \sim N\left(0, \sigma_{v_{10k}}^2\right)$$

Declercq, L., Jamshidi, L., Fernandez Castilla, B., Moeyaert, M., Beretvas, S. N., Ferron, J. M., & Van den Noortgate, W. (2022). Multilevel meta-analysis of individual participant data of single-case experimental designs: One-stage versus two-stage methods. *Multivariate Behavioral Research, 57*(2-3), 298-317.

2. Empirical Validation:

Monte Carlo Simulation Study

Purpose:

- Statistical properties of IPD meta-analysis of multiple-baseline design data using three-level modeling.
- Empirically investigate under which realistic SCED conditions intervention and moderator effects can be estimated with appropriate statistical properties.

Design Factor	Notation	Value
Number of studies	K	10, 30, 40 or 50
Number of observations	I	20 or 40
Number of participants	J	4, 7, 12
Intervention effect	γ_{100}	0 or 2
Moderator effects	Gender, γ_{110}	0.75, 1.00, 1.50, 2.00
	Age, γ_{120}	0.25 or 0.50
	Study Quality, γ_{101}	0.75, 1.00, 1.50, 2.00
	Physical Setting, γ_{102}	0.75, 1.00, 1.50, 2.00
Between-case variance	Baseline level, $\sigma^2_{\theta 0}$	2.00
	Intervention effect, $\sigma^2_{\theta 1}$	2.00
Between-study variance	Baseline level, $\sigma^2_{\theta 0}$	2.00
	Intervention effect, $\sigma^2_{\theta 1}$	2.00
Within-participant variance	σ^2_e	1.00

Moeyaert, M., Yang, P., Xu, X., & Kim, E. (2021). Characteristics of moderators in meta-analyses of single-case experimental design studies. *Behavior Modification*. https://doi.org/10.1177/01454455211002111

3. Methodological Research

Simulation Study – Data Generation

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(1) **Model 0**: No Moderators

$$Y_{ijk} = \gamma_{000} + v_{00k} + u_{0jk} + (\gamma_{100} + v_{10k} + u_{1jk})D_{ijk} + e_{ijk}$$

(2) **Model 1**: One Moderator at Level 2 and One Moderator at Level 3

$$Y_{ijk} = \gamma_{000} + v_{00k} + u_{0jk} + (\gamma_{100} + \gamma_{110}\boldsymbol{Gender_{11k}} + \gamma_{101}\boldsymbol{Quality_{101}} + v_{10k} + u_{1jk})D_{ijk} + e_{ijk}$$

(3) **Model 2**: Two Moderators at Level 2 and One Moderator at Level 3

$$Y_{ijk} = \gamma_{000} + v_{00k} + u_{0jk} + (\gamma_{100} + \gamma_{110}\boldsymbol{Gender_{11k}} + \gamma_{120}\boldsymbol{Age_{11k}} + \gamma_{101}\boldsymbol{Quality_{101}} + v_{10k} + u_{1jk})D_{ijk} + e_{ijk}$$

(4) **Model 3**: Two Moderators at Level 2 and Two Moderators at Level 3

$$Y_{ijk} = \gamma_{000} + v_{00k} + u_{0jk} + (\gamma_{100} + \gamma_{110}\boldsymbol{Gender_{11k}} + \gamma_{120}\boldsymbol{Age_{11k}} + \gamma_{101}\boldsymbol{Quality_{101}} + \gamma_{102}\boldsymbol{Setting_{101}} + v_{10k} + u_{1jk})D_{ijk} + e_{ijk}$$

3. Methodological Research

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Simulation Study – Data Generation

- The number of conditions investigated depends on the specific model of interest.
- Model 0 is the only model that does not include 40 or 50 studies. The reason for this is that statistical properties are appropriate with as few as 30 studies (and there is already sufficient power across all conditions with 30 studies).
- Number of conditions per model:
  - **Model 0**: 2 × 2 × 3 × 2 = 24 conditions,
  - **Model 1**: 4 × 2 × 3 × 2 × 4 × 4 = 768 conditions,
  - **Model 2**: 4 × 2 × 3 × 2 × 4 × 2 × 4 = 1,536 conditions
  - **Model 3**: 4 × 2 × 3 × 2 × 4 × 2 × 4 × 4 = 6,144 conditions.

- 4 conditions for *Number of Studies*
- 2 conditions for *Number of Observations*
- 3 conditions for *Number of Participants*
- 2 conditions for *Intervention Effect*
- 4 conditions for *Magnitude of Gender Effect*
- 4 conditions for *Magnitude of Study Quality Effect*

3. Methodological Research

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Simulation Study – Data Generation

- The number of conditions investigated depends on the specific model of interest.
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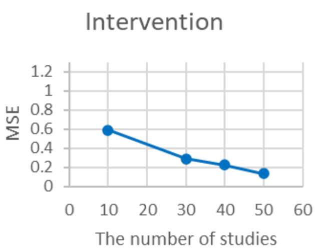
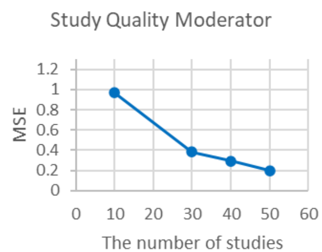
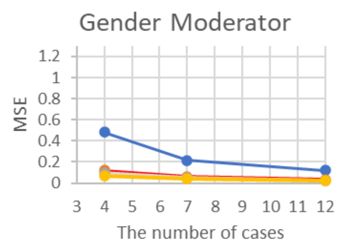
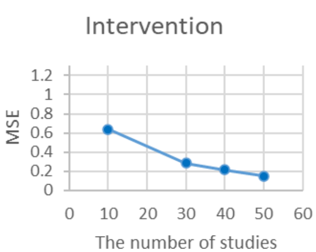
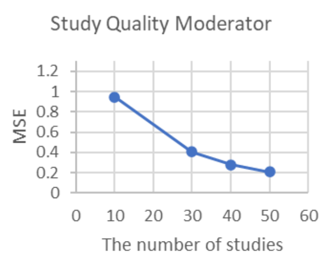
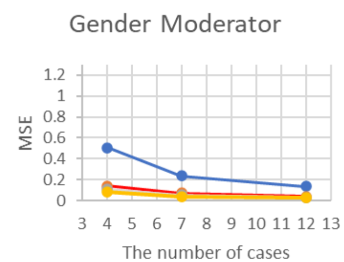
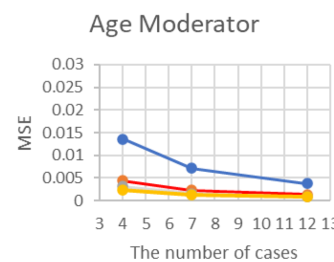
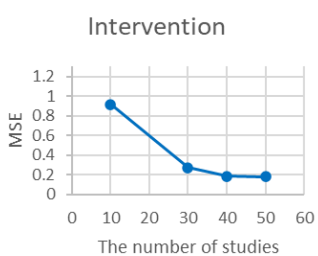
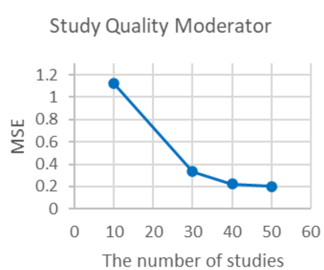
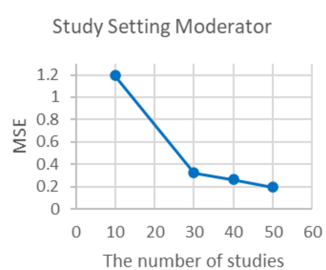
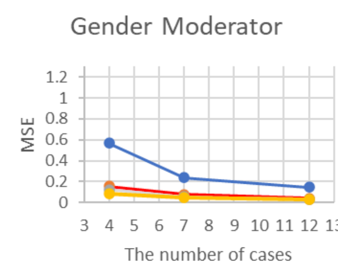
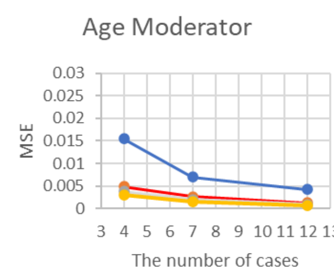
- Number of conditions per model:
  - **Model 0**: $2 \times 2 \times 3 \times 2 = 24$ conditions,
  - **Model 1**: $4 \times 2 \times 3 \times 2 \times 4 \times 4 = 768$ conditions,
  - **Model 2**: $4 \times 2 \times 3 \times 2 \times 4 \times 2 \times 4 = 1{,}536$ conditions
  - **Model 3**: $4 \times 2 \times 3 \times 2 \times 4 \times 2 \times 4 \times 4 = 6{,}144$ conditions.
- For each condition, 1,000 datasets are examined. This resulted in a total of 8,472,000 datasets to be examined
  - $(24 + 768 + 1{,}536 + 6{,}144) \times 1{,}000 = 8{,}472{,}000$ datasets.

3. Methodological Research

Simulation Study - Results

	MSE as a function of number of studies	*MSE as a function of number of studies and cases*
Model 1	 	 K = 10, K = 30, K = 40, K = 50 **(Same for the figures below)**
Model 2	 	 
Model 3	  	 

3. Methodological Research

Simulation Study - Results

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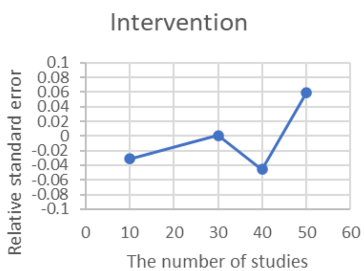
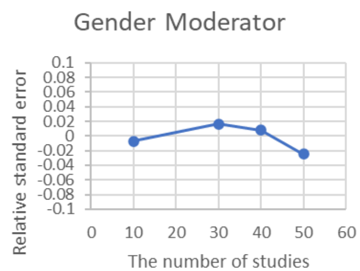
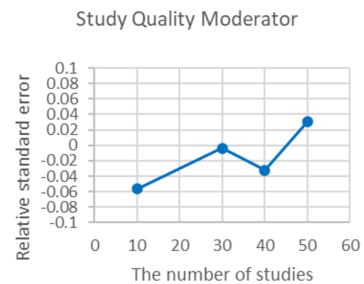
Relative Standard Error Bias as a function of number of studies

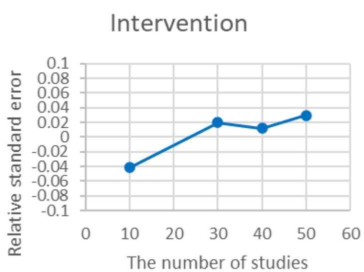
Model 1

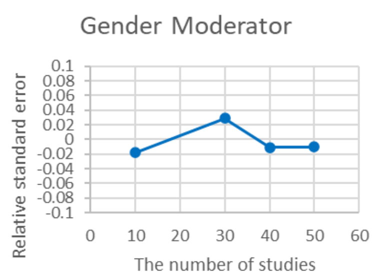


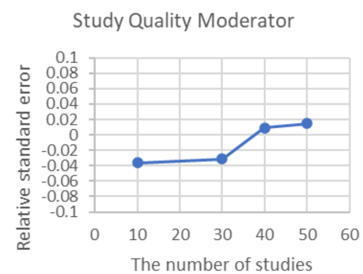




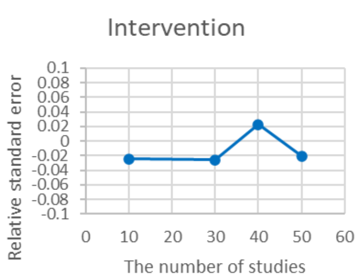
Model 2

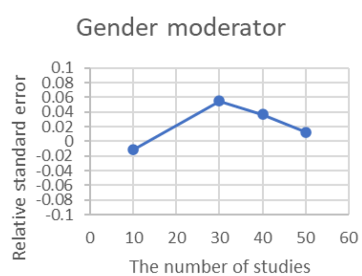


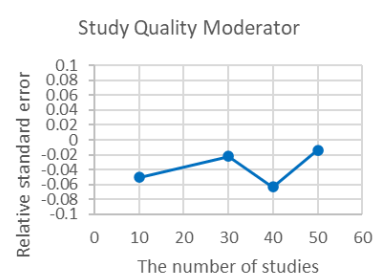


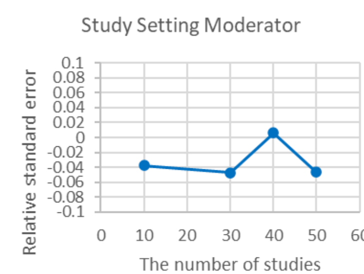


Model 3







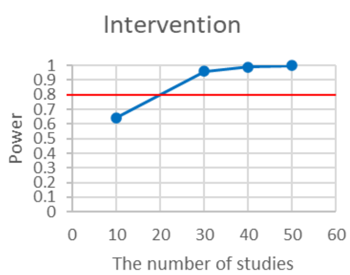


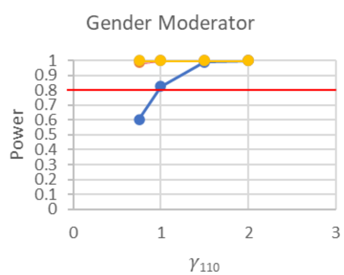
3. Methodological Research

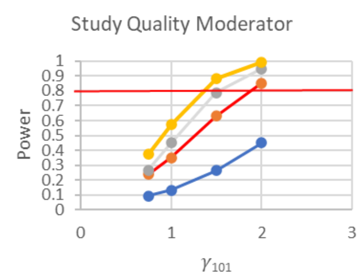
Simulation Study - Results

Power as a function of number of studies | *Power as a function of number of studies and Gender/Study Quality/Study Setting moderator effect*

Model 1

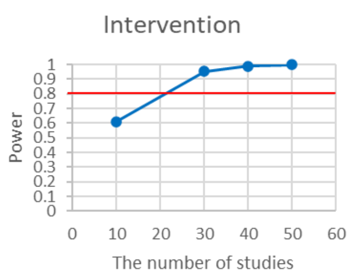


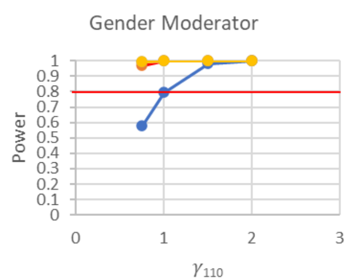


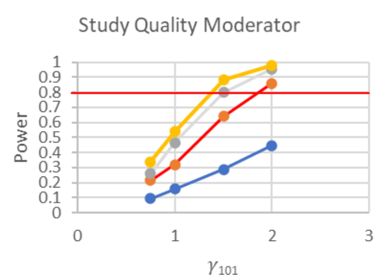


K = 10 K = 30
K = 40 K = 50
(Same for the figures below)

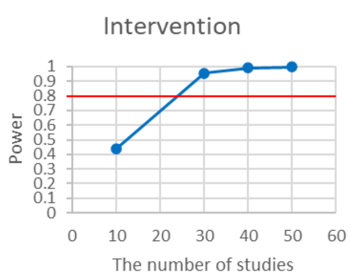
Model 2

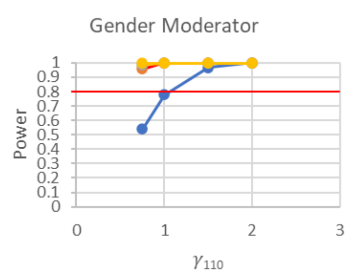


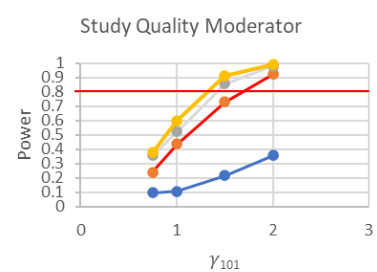


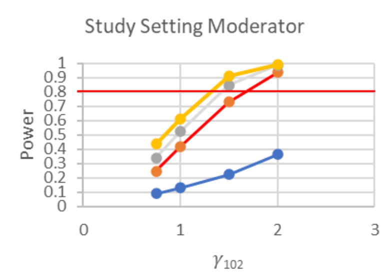


Model 3









4. Conclusion

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- The impact of unit changes within the three-level modeling varies across different levels.
  - Unit changes at the **level 3** (number of studies) and at **level 2** (number of participants) tend to have larger influences on the statistical properties when compared to changes at the lower level, **level 1** (number of measurement occasions).
- When the number of studies is large ($k \geq 30$), the statistical properties of intervention and moderator effect estimates are appropriate, regardless of the number of participants, number of measurement occasions, and the magnitude of intervention and moderator effects.
- The only exception: for estimating the level 3 moderators (i.e., study quality and study setting), a substantial effect size is required in conjunction with a minimum of 30 studies.
- We do not recommend using IPD meta-analysis, with the inclusion of moderators, when the number of studies is small ($k = 10$).

4. Future Research

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- Extending the basic three-level model introduced in this study by including more complexities (e.g., models with linear/non-linear time trends; imbalanced moderators; autocorrelation; count outcomes).
- Evaluating the robustness of IPD meta-analysis against violation of modeling assumptions such as non-normality of residuals.
- Dealing with situations when less studies are included for a meta-analysis.

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Thank you for listening.

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