- Meta-analytic findings of the self-controlled motor learning literature:
- Underpowered, biased, and lacking evidential value
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In Press in Meta-Psychology

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1 Abstract

The self-controlled motor learning literature consists of experiments that compare a group of learners who are provided with a choice over an aspect of their practice environment to a group who are yoked to those choices. A qualitative review of the literature suggests an unambiguous benefit from self-controlled practice. A meta-analysis was conducted on the effects of self-controlled practice on retention test performance measures with a focus on assessing and potentially correcting for selection bias in the literature, such as publication bias and p-hacking. First, a naïve random effects model was fit to the data and a moderate benefit of self-controlled practice, q = .44 (k = 52, N = 2061, 95% CI [.31, .56]), was found. Second, publication status was added to the model as a potential moderator, revealing a significant difference between published and unpublished findings, with only the former reporting a benefit of self-controlled practice. Third, to investigate and adjust for the impact of selectively reporting statistically significant results, a weight-function model 13 was fit to the data with a one-tailed p-value cutpoint of .025. The weight-function model 14 revealed substantial selection bias and estimated the true average effect of self-controlled 15 practice as g = .107 (95% CI [.047, .18]). P-curve analyses were conducted on the 16 statistically significant results published in the literature and the outcome suggested a lack 17 of evidential value. Fourth, a suite of sensitivity analyses were conducted to evaluate the 18 robustness of these results, all of which converged on trivially small effect estimates. 19 Overall, our results suggest the benefit of self-controlled practice on motor learning is small 20 and not currently distinguishable from zero. 21

*Keywords:* Motor learning, retention, choice, "OPTIMAL" theory, meta-analysis, p-curve, publication bias

Asking learners to control any aspect of their practice environment has come to be known as self-controlled practice in the motor learning literature (Sanli, Patterson, Bray, & Lee, 2013; Gabriele Wulf & Lewthwaite, 2016). The first published experiments to test self-controlled learning asked learners to control their augmented feedback schedule (Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995). For example, in an experiment by Janelle, Barba, Frehlich, Tennant, and Cauraugh (1997), participants practiced throwing tennis balls at a target with their non-dominant hand. The practice period occurred over two separate days. Participants were assigned to one of four experimental groups (n = 12): Self-controlled knowledge of performance, voked-to-self-control, summary knowledge of performance after every five trials, and a 10 knowledge of results only control group. The self-controlled group could request knowledge 11 of performance whenever they wanted it, while each yoked group participant was matched with a self-control group counterpart and received knowledge of performance on the same 13 schedule. The experimenter evaluated the participants' throws, identified the most critical error in their throwing form, and provided knowledge of performance via video feedback, 15 along with directing attention to the error and giving prescriptive feedback. During a 16 delayed-retention test, the accuracy, form, and speed of the throw were assessed. The results indicated that the self-control group threw more accurately and with better form 18 than all other groups on the retention test. The self-control and yoked groups did not 19 significantly differ in throwing speed, but the control group threw faster than the 20 self-control group on the second retention block. The results were interpreted as evidence 21 that the participants provided with choice were able to process information more efficiently than their counterparts who received a fixed schedule of feedback. 23 Figure 1 shows that the number of experiments comparing self-controlled groups to 24 voked groups has been increasing since the original experiments by Janelle and his 25 colleagues (1997; 1995). Researchers have experimented with giving learners control over a

variety of variables in the practice environment. A qualitative assessment of the literature

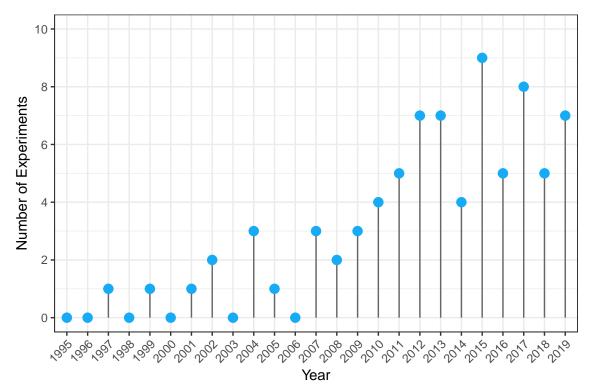


Figure 1

Number of self-controlled learning experiments meeting the inclusion criteria by year.

- suggests that self-control is generally beneficial regardless of choice-type (Gabriele Wulf &
- Lewthwaite, 2016). For example, self-control has been effective when participants have
- been provided choice over what can be considered instructionally-relevant variables, such as
- 4 knowledge of results (Patterson & Carter, 2010), knowledge of performance (Lim et al.,
- 5 2015), concurrent feedback (Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009), use
- of an assistive device (G. Wulf, Clauss, Shea, & Whitacre, 2001), observation of a skilled
- model (Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017), practice schedule (Will F. W.
- <sup>8</sup> Wu & Magill, 2011), practice volume (Lessa & Chiviacowsky, 2015), and task difficulty
- 9 (Leiker et al., 2016). Additionally, self-controlled benefits have also been found for
- instructionally-irrelevant variables, such as: the colour of various objects in the practice
- environment (Gabriele Wulf et al., 2018), other decorative choices (Iwatsuki, Navalta, &
- Wulf, 2019), and the choice of what to do after the retention test is complete (Lewthwaite,

<sup>1</sup> Chiviacowsky, Drews, & Wulf, 2015).

Despite the widespread optimism that self-controlled practice is useful for enhancing 2 motor learning, researchers continue to debate the underlying mechanisms responsible for the effect (M. J. Carter & Ste-Marie, 2017b; Gabriele Wulf et al., 2018). Beginning with Janelle, Kim, and Singer (1995), both motivational and information processing mechanisms were proposed as possible explanations for self-control benefits. Researchers have since supported these two mechanisms and, from a motivational perspective, have posited that self-control enhances confidence (Chiviacowsky, Wulf, & Lewthwaite, 2012; Janelle, Kim, & Singer, 1995; Gabriele Wulf & Lewthwaite, 2016) and satisfies the basic psychological need for autonomy (Sanli, Patterson, Bray, & Lee, 2013; Gabriele Wulf & Lewthwaite, 2016), motivating motor performance and learning enhancement. Most self-controlled learning experiments, however, have involved participants making choices over potentially 12 informative variables, which could act as a confounding variable. Citing this potential 13 motivational/informational confound, Lewthwaite, Chiviacowsky, Drews, and Wulf (2015) 14 experimented with providing instructionally-irrelevant choices, such as the colour of the 15 golf balls to putt, the painting to hang on the wall, and what to do following the retention 16 test. Lewthwaite and her colleagues reasoned that information processing explanations 17 could not account for benefits due to these incidental choices, and instead motivational 18 factors would be more likely. Consistent with the motivational hypothesis, participants 19 exhibited significantly greater motor learning on a golf putting task (Experiment 1) and on a balance task (Experiment 2). Subsequently, several experiments have reported benefits 21 with instructionally-irrelevant choices (Abdollahipour, Palomo Nieto, Psotta, & Wulf, 22 2017; Chua, Wulf, & Lewthwaite, 2018; Halperin, Chapman, Martin, Lewthwaite, & Wulf, 23 2017; Iwatsuki, Navalta, & Wulf, 2019; Gabriele Wulf, Chiviacowsky, & Cardozo, 2014; Gabriele Wulf et al., 2018), further reinforcing this motivational perspective. 25

A contrasting line of research has been reported by Carter and his colleagues (2014; 2017a, 2017b) in which informational factors, the second dominant perspective, are given

- more weight as an explanatory variable. In one experiment by M. J. Carter, Carlsen, and Ste-Marie (2014), self-control participants were provided with choice over receiving knowledge of results, but divided into three experimental groups; those who could make their knowledge of results decision: before the trial, after the trial, or both (they would decide before, but could change their mind following the trial). Timing of the choice significantly attenuated the self-control benefit. While the self-after and self-both groups exhibited learning advantages relative to their voked counterparts, the self-before group displayed no such advantage. The argument proffered by the researchers was that there was more informational value to be gained from knowledge of results requested after a trial than when it had to be requested before the outcome of the trial occurred (also see 10 Chiviacowsky & Wulf, 2005). 11 In another experiment (M. J. Carter & Ste-Marie, 2017a), asking learners to
- 12 complete an interpolated activity in the interval preceding their choice of whether to 13 receive knowledge of results significantly attenuated the self-control benefit (also see 14 Couvillion, Bass, & Fairbrother, 2020; Woodard & Fairbrother, 2020). As a final example, 15 M. J. Carter and Ste-Marie (2017b) compared an instructionally-relevant choice group (i.e., 16 when to receive knowledge of results) to an instructionally-irrelevant choice group (i.e., 17 which video game to play after retention and which colour arm wrap to wear while 18 practicing). Unlike the experiment by Wulf and colleagues (2018), Carter and Ste-Marie 19 found that instructionally-relevant choices were more effective than task-irrelevant choices. Overall, they have used these different findings to tie self-controlled learning benefits to 21 information-processing activities of the learner and, in particular, those related to the processing of intrinsic feedback (e.g., M. J. Carter & Ste-Marie, 2017a; Chiviacowsky & 23 Wulf, 2005) and the provided knowledge of results (e.g., Grand et al., 2015). In the present research, these different viewpoints concerning the mechanisms of
- 25 self-controlled learning advantages were examined via meta-analysis with choice-type included as a moderator. The logic was that the motivational and informational

- perspectives would have different predictions. More specifically, from a motivation
- 2 hypothesis, no moderating effect of choice-type on motor learning would be expected. In
- 3 contrast, smaller effects for irrelevant-choice type, as compared to relevant-choice types,
- 4 would be expected from the information-processing perspective.
- Beyond this interest in the possible theoretical mechanisms, a more important
- 6 question addressed was whether there is in fact evidential value for the self-controlled
- <sup>7</sup> learning benefit. This is of relevance because the current consensus in the field is that
- self-controlled practice is generally more effective than yoked practice (for reviews see
- 9 Sanli, Patterson, Bray, & Lee, 2013; Ste-Marie, Carter, & Yantha, 2019; Gabriele Wulf &
- Lewthwaite, 2016). Reflecting this confidence in its benefits for motor learning, researchers
- have recommended adoption of self-control protocols in varied settings, such as medical
- training (Brydges, Carnahan, Safir, & Dubrowski, 2009; Jowett, LeBlanc, Xeroulis,
- MacRae, & Dubrowski, 2007; Gabriele Wulf, Shea, & Lewthwaite, 2010), physiotherapy
- (Hemayattalab, Arabameri, Pourazar, Ardakani, & Kashefi, 2013; Gabriele Wulf, 2007),
- music pedagogy (Gabriele Wulf & Mornell, 2008), strength and conditioning (Halperin,
- Wulf, Vigotsky, Schoenfeld, & Behm, 2018), and sports training (Janelle, Kim, & Singer,
- 17 1995; Sigrist, Rauter, Riener, & Wolf, 2013).
- Problematic though is that recent, high-powered experiments with pre-registered
- analysis plans have failed to observe motor learning or performance benefits with
- self-control protocols (Grand, Daou, Lohse, & Miller, 2017; McKay & Ste-Marie, 2020; St.
- Germain et al., 2021; Yantha, 2019). Against the backdrop of the so-called replication
- crisis in psychology (Open Science Collaboration, 2015), there is reason for pause when
- evaluating the ostensible benefits of self-controlled learning. Further, Lohse, Buchanan,
- 24 and Miller (2016) have raised concerns about publication bias, uncorrected multiple
- 25 comparisons, p-hacking, and other selection effects in the motor learning literature.
- 26 Therefore, to address the impact of selection effects on estimates of the self-controlled
- learning effect, a weight function model (E. C. Carter, Schönbrodt, Gervais, & Hilgard,

- 2019; Hedges & Vevea, 1996; McShane, Böckenholt, & Hansen, 2016; Vevea & Hedges,
- <sup>2</sup> 1995; Vevea & Woods, 2005) with a one-tailed p-value cutpoint of .025 was fit to the
- dataset of effects to provide a pre-registered adjusted estimate of the overall self-controlled
- 4 learning effect. Even the adjusted estimate is biased if the data generating processes are
- biased in ways not captured by the assumptions of the model, so further sensitivity
- 6 analyses were conducted to estimate the average effect of self-control after correcting for
- <sup>7</sup> selection effects (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019; Vevea & Woods,
- 8 2005). In parallel, in an effort to investigate the presence of evidential value in the
- 9 literature, significant results were subjected to a p-curve analysis (Simonsohn, Nelson, &
- Simmons, 2014a; Simonsohn, Simmons, & Nelson, 2015). The p-curve analysis focuses
- exclusively on significant results and therefore is not affected by publication bias.

In sum, the objectives of this meta-analysis were to estimate the true average effect 12 of self-controlled learning and evaluate the evidential value of the self-controlled learning 13 literature. Bias resulting from selective publication was addressed with weight function and 14 p-curve models and effect size estimates were adjusted accordingly. A key theoretical 15 question related to the underlying mechanisms of putative self-controlled learning 16 advantages (motivational versus informational influences) was also addressed through 17 moderator analyses, but, to anticipate, inferences will depend on the reliability of the 18 evidence overall. Finally, sensitivity analyses were conducted in addition to pre-registered 19 analyses in an effort to understand the extent that our conclusions depended on the 20 modeling techniques and assumptions adopted. 21

22 Method

### 23 Pre-registration

The procedures followed to conduct this meta-analysis were pre-registered and can be viewed at https://osf.io/qbg69 (see Data, materials, and code availability section). This

- meta-analysis was retrospective and earlier samples of the literature had been
- <sup>2</sup> meta-analyzed prior to this pre-registration, albeit with different data collection
- procedures, scope, and excluding recent experiments. This study adheres to PRISMA
- 4 reporting guidelines (Page et al., 2021).

### 5 Literature search

- The literature search and data extraction were conducted by three authors (BM, ZY, JH) and one research assistant (HS) independently. The goal of the search was to identify all articles that met the inclusion criteria for the meta-analysis. Specifically, randomized experiments were subject to five criteria for inclusion: 1) A self-control group in which participants were asked to make at least one choice during practice, 2) a voked group 10 that experienced the same practice conditions as the self-controlled group, 3) a delayed 11 ~24-hour retention test or test with longer delay interval, 4) an objective measurement of 12 motor performance, and 5) publication in a peer-reviewed journal or acceptance as part of 13 a Master's or PhD thesis. The literature search was completed on August 2, 2019. 14 The search commenced at PubMed and Google Scholar with the following query: 15 \*self-control\*\* OR \*self-regulat\*\* OR \*self-direct\*\* OR \*learner-control\*\* OR 16 \*learner-regulat\*\* OR \*learner-direct\*\* OR \*subject-control\*\* OR \*subject-regulat\*\* OR 17 \*subject-direct\*\* OR \*performer-control\*\* OR \*performer-regulat\*\* OR 18 \*performer-direct\*\* AND \*motor learning\*\*. The query retrieved 9014 hits on PubMed 19 and 98,600 hits on Google Scholar. Each researcher excluded hits based on title alone or 20 title and abstract when necessary, and quit searching the databases at self-selected 21 intervals following extended periods of excluding 100% of search results. Following an initial run of searching databases, each researcher employed their own search strategies, including reviewing the reference sections of reviews and included articles, consulting the
  - <sup>1</sup> The webpage link that was consulted (https://optimalmotorlearning.com/index.php/did-you-know-that/)

"OPTIMAL" theory website<sup>1</sup>, and searching the ProQuest Thesis database.

This literature search process resulted in 160 articles that could not be excluded without consulting the full-text of the article. All 160 articles were coded for inclusion or exclusion by two researchers independently. All instances of disagreement between coders were reviewed by three authors (BM, ZY, and JH), and consensus was reached in each case. Disagreements were infrequent and were often caused by a lack of clarity in the articles (e.g., 100% knowledge of results groups labeled as yoked groups). None of the coding disagreements evolved into conceptual disagreements. Rather, in each case, it was identified that one coder had missed a detail in the full text that changed its inclusion eligibility. Subsequent to this process, a total of 73 articles, which included 78 experiments, met the inclusion criteria (see Table 1).

# 1 Dependent variable selection

The focus of this meta-analysis was on performance outcomes associated with the 12 goal of the skill. The primary theoretical perspectives offered as an account for 13 self-controlled learning are likewise focused on performance outcomes. For example, the 14 "OPTIMAL" theory proposes that a learner's movements become coupled with the goal 15 they are trying to achieve when they experience autonomy-support during practice 16 (Gabriele Wulf & Lewthwaite, 2016). To reflect this focus, a dependent measure priority 17 list was developed that gave higher priority to absolute error measures and less priority to 18 consistency measures, time/work measures, and form scores. Dependent measure priority 19 was ordered as follows: 1) absolute error (and analogous measures: radial error, points in 20 an accuracy measure), 2) root-mean-square-error (RMSE), 3) absolute constant error, 4) 21 variable error, 5), movement time (and distance travelled), 6) movement form – expert 22 raters, 7) otherwise unspecified objective performance measure reported first in research is no longer available. A new webpage devoted to "OPTIMAL" theory can be accessed using the following link: https://gwulf.faculty.unlv.edu/optimal-motor-learning/.

- report.<sup>2</sup> In the event that multiple measures of motor performance were reported for an
- <sup>2</sup> experiment, effect sizes were calculated for the highest priority measure reported in the
- 3 study. In experiments with multiple self-control groups and one yoked group, the
- 4 self-control groups were combined (J. P. Higgins & Green, 2011). If multiple choice-types
- or sub-populations were included in an experiment, combined and individual effects were
- 6 calculated for inclusion in moderator analyses.

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Many of the self-controlled learning experiments analyzed in this study included multiple dependent measures. However, including multiple measures from the same experiment introduces bias and inflates Type 1 error (Scammacca, Roberts, & Stuebing, 2014). Although there are a variety of methods for dealing with multiple measures from the same studies in meta-analysis, we chose to create a priority list and always selected the highest priority dependent measure that was reported. If the highest priority measure was not described in adequate detail to calculate the effect size, the authors were contacted and the data were requested. If the authors could not provide the data for the highest priority

dependent measure reported in their study, the experiment was left out of our analysis.

The rationale for selecting the approach we did was based on five considerations.

First, our interest was in motor learning as reflected by an enhanced capability to perform
a skill. Motor learning studies often report multiple error measures, but they are not
equally coupled with performance outcome. Constant error, for example, was not included
on the priority list because it is possible to have zero constant error while performing
terribly overall. Therefore, we chose to prioritize measures that could be considered to be
tightly coupled with performance, like absolute error, RMSE, and absolute constant error.

If these measures were not used, measures that are only correlated with performance, such
as variable error, movement time, and movement form, were selected. We reasoned this

<sup>&</sup>lt;sup>2</sup> Radial error, accuracy points, and distance travelled were added to the pre-registered dependent measures as they arose during data-extraction. Decisions were made blind to the data by an author not involved in said extraction (BM or DSM).

selection strategy would focus the analysis on measures related to improved skill while de-emphasizing other effects. Second, we reasoned that averaging across dependent measures could introduce additional heterogeneity to the analysis by including potentially disparate dependent measures. The third, fourth, and fifth considerations all relate to avoiding bias but differ with regard to the source of the bias and the alternate method that would include such bias. Thus, the third consideration was that imposing a priority list was thought to better avoid biases that could emerge from selecting the most focal measure in a given study, because an unknowable percentage of studies may have defined the focal measure based on the strength of the findings. Fourth, we reasoned that some measures may only get reported if they support the predicted benefit of self-control. Scammacca, 10 Roberts, and Stuebing (2014) reported that effect size estimates were inflated when 11 random dependent measures were selected in a meta-analysis case study, perhaps reflecting a selective reporting bias. Averaging across all reported measures—a fair alternative to our approach—could conceivably pick up some of this reporting bias. Fifth, we ignored lower priority measures with data when higher priority measures lacked data because we 15 reasoned there could be a systematic reason for this pattern: preference for reporting data 16 associated with positive effects. Indeed, there were articles where the only measure 17 reported with sufficient data to calculate an effect size was also the only measure with a 18 significant result (e.g., Gabriele Wulf, Raupach, & Pfeiffer, 2005). 19

#### 20 Data extraction

The four researchers separated into pairs and half of the included experiments were coded independently by one pair. The other half were coded independently by the other pair. The coding included varied moderators, publication year, and sample size. Also Hedges' g was calculated from reported statistics and sample size using the compute.es package (Re, 2013) in R (R Core Team, 2021). Effect sizes were calculated from means and standard deviations, test statistics like t and F, or from precisely reported p-values. When

- covariates were included in the analysis, the correlation coefficient for the covariate -
- <sup>2</sup> dependent measure relationship was required to calculate accurate effect sizes. Since this
- 3 information is often not reported, authors were contacted and the information was
- requested. One effect size was calculated for each of three time points for each experiment:
- <sup>5</sup> Acquisition, retention, and transfer.

Table 1

Experiment characteristics and moderator coding.

Authors	Year	Setting	Compensation	Choice-type	Population	Retention	N	Published
Aiken et al.	2012	Applied	Not stated	Observation	Adult	24-hr	28	Yes
Alami	2013	Lab	Yes	Feedback (KR)	Adult	24-hr	22	No
Ali et al.	2012	Lab	Not stated	Feedback (KR)	Adult	24-hr	48	Yes
Andrieux et al.	2016	Lab	Not stated	Task difficulty	Adult	24-hr	48	Yes
Andrieux et al.	2012	Lab	Not stated	Task difficulty	Adult	24-hr	38	Yes
Arsal	$2004,\mathrm{Exp}\ 1$	Lab	Not stated	Feedback (KR)	Adult	48-hr	28	No
Arsal	2004, Exp 2	Lab	Not stated	Feedback (KR)	Adult	48-hr	28	No
Barros	2010, Blocked	Lab	Not stated	Feedback (KR)	Adult	24-hr	48	No
Barros	2010, Random	Lab	Not stated	Feedback (KR)	Adult	24-hr	48	No
Barros et al.	2019, Exp 1	Lab-Applied	No	Feedback (KR)	Adult	24-hr	60	Yes
Barros et al.	2019, Exp 2	Lab	No	Feedback (KR)	Adult	24-hr	60	Yes
Bass	2015	Lab	No	Feedback (KR)	Adult	24-hr	20	No
Bass	2018	Applied	No	Feedback (KR)	Adult	24-hr	60	No
Brydges et al.	2009	Applied	Not stated	Observation	Adult	>48-hr	48	Yes
Bund & Weimeyer	2004	Lab-Applied	No	Observation	Adult	24-hr	52	Yes

Carter & Patterson	2012	Lab	Not stated	Feedback (KR)	Adult	24-hr	20	Yes
Carter & Patterson	2012	Lab	Not stated	Feedback (KR)	Older	24-hr	20	Yes
Carter & Patterson	2012	Lab	Not stated	Feedback (KR)	Two	24-hr	40	Yes
Chen et al.	2002	Lab	Yes	Feedback (KR)	Adult	48-hr	48	Yes
Chiviacowsky	2014	Lab	Not stated	Feedback (KR)	Adult	24-hr	28	Yes
Chiviacowsky & Lessa	2017	Lab	Not stated	Feedback (KR)	Oider	48-hr	22	Yes
Chiviacowsky & Wulf	2002	Lab	Not stated	Feedback (KR)	Adult	24-hr	30	Yes
Chiviacowsky et al.	2012	Lab	Not stated	Feedback (KR)	Clinical	24-hr	30	Yes
Chiviacowsky et al.	2008	Lab	Not stated	Feedback (KR)	Children	24-hr	26	Yes
Chiviacowsky et al.	2012	Lab	Not stated	Assistive device	Clinical	24-hr	28	Yes
Davis	2009	Applied	Not stated	Model	Adult	24-hr	24	No
Fagundes et al.	2013	Lab-Applied	Not stated	Feedback (KR)	Adult	48-hr	52	Yes
Fairbrother et al.	2012	Lab	Not stated	Feedback (KR)	Adult	24-hr	48	Yes
Ferreira et al.	2019	Lab	Not stated	Feedback (KR)	Adult	24-hr	60	Yes
Figueiredo et al.	2018	Lab	No	Feedback (KR)	Adult	24-hr	30	Yes
Ghorbani	2019, Exp 2	Lab-Applied	Not stated	Feedback (KR)	Adult	24-hr	36	Yes
Grand et al.	2015	Lab	No	Feedback (KR)	Adult	24-hr	36	Yes
Grand et al.	2017	Lab	Yes	Incidental	Adult	>48-hr	68	Yes

Hansen et al.	2011	Lab	No	Feedback (KR)	Adult	24-hr	24	Yes
Hartman	2007	Lab	Not stated	Assistive device	Adult	24-hr	18	Yes
Hemayettalab et al.	2013	Lab	Not stated	Feedback (KR)	Clinical	24-hr	20	Yes
Но	2016	Lab	Not stated	Amount of practice	Adult	24-hr	120	No
Holmberg	2013	Lab-Applied	No	Feedback (KP)	Adult	24-hr	24	No
Huet et al.	2009	Lab-Applied	Not stated	Feedback (Concurrent)	Adult	24-hr	20	Yes
Ikudome et al.	2019, Exp 1	Lab-Applied	No	Incidental	Adult	24-hr	40	Yes
Ikudome et al.	2019, Exp 2	Lab-Applied	No	Observation	Adult	24-hr	40	Yes
Jalalvan et al.	2019	Lab-Applied	Not stated	Task difficulty	Adult	24-hr	60	Yes
Janelle et al.	1997	Lab-Applied	Yes	Feedback (KP)	Adult	>48-hr	48	Yes
Jones	2010	Lab	Yes	Repetition schedule	Adult	24-hr	40	No
Kaefer et al.	2014	Lab	No	Feedback (KR)	Adult	24-hr	56	Yes
Keetch & Lee	2007	Lab	Yes	Repetition schedule	Adult	24-hr	96	Yes
Kim et al.	2019	Lab	Yes	Feedback (KR)	Adult	24-hr	42	Yes
Leiker et al.	2016	Lab-Applied	Not stated	Task difficulty	Adult	>48-hr	60	Yes
Leiker et al.	2019	Lab	Not stated	Task difficulty	Adult	>48-hr	60	Yes
Lemos et al.	2017	Applied	No	Observation	Children	24-hr	24	Yes
Lessa & Chiviacowsky	2015	Applied	Not stated	Amount of practice	Older	48-hr	36	Yes

Lewthwaite et al.	$2015,\mathrm{Exp}\ 1$	Lab-Applied	Not stated	Incidental	Adult	24-hr	24	Yes
Lewthwaite et al.	$2015,\mathrm{Exp}\ 2$	Lab	Not stated	Incidental	Adult	24-hr	30	Yes
Lim et al.	2015	Applied	Not stated	Feedback (KP)	Adult	24-hr	24	Yes
Marques & Correa	2016	Applied	Not stated	Feedback (KP)	Adult	48-hr	70	Yes
Marques et al.	2017	Applied	Not stated	Feedback (KP)	Adult	24-hr	30	Yes
Norouzi et al.	2016	Lab	Not stated	Feedback (KR)	Adult	24-hr	45	Yes
Nunes et al.	2019	Lab-Applied	No	Feedback (KP)	Older	24-hr	40	Yes
Ostrowski	2015	Lab	Not stated	Feedback (KR)	Adult	24-hr	80	No
Patterson & Carter	2010	Lab	Yes	Feedback (KR)	Adult	24-hr	24	Yes
Patterson & Lee	2010	Lab-Applied	Yes	Task difficulty	Adult	48-hr	48	Yes
Patterson et al.	2013	Lab	Yes	Feedback (KR)	Adult	24-hr	48	Yes
Patterson et al.	2011	Lab	Yes	Feedback (KR)	Adult	24-hr	60	Yes
Post et al.	2016	Lab-Applied	No	Feedback (KP)	Adult	24-hr	44	Yes
Post et al.	2011	Applied	No	Amount of practice	Adult	24-hr	24	Yes
Post et al.	2014	Applied	Not stated	Amount of practice	Adult	24-hr	30	Yes
Rydberg	2011	Applied	Not stated	Repetition schedule	Adult	24-hr	16	No
Sanli & Patterson	2013	Lab	No	Repetition schedule	Adult	24-hr	24	Yes
Sanli & Patterson	2013	Lab	No	Repetition schedule	Children	24-hr	24	Yes

Ste-Marie et al.	2013	Applied	No	Feedback (KP)	Children	24-hr	60	Yes
Tsai & Jwo	2015	Lab	Yes	Feedback (KR)	Adult	24-hr	36	Yes
von Lindern	2017	Lab	Not stated	Feedback (KR)	Adult	24-hr	48	No
Williams et al.	2017	Lab	Yes	Feedback (Concurrent)	Adult	24-hr	29	Yes
Wu & Magill	2011	Lab	No	Repetition schedule	Adult	24-hr	30	Yes
Wu	2007, Exp 1	Lab-Applied	Yes	Repetition schedule	Adult	24-hr	30	No
Wulf & Adams	2014	Lab	No	Repetition schedule	Adult	24-hr	20	Yes
Wulf &Toole	1999	Lab-Applied	Yes	Assistive device	Adult	24-hr	26	Yes
Wulf et al.	$2015,\mathrm{Exp}\ 1$	Lab-Applied	No	Repetition schedule	Adult	24-hr	68	Yes
Wulf et al.	2001	Lab-Applied	Yes	Assistive device	Adult	24-hr	26	Yes
Wulf et al.	$2018,\mathrm{Exp}\ 1$	Lab-Applied	No	Incidental	Adult	24-hr	32	Yes
Wulf et al.	$2018,\mathrm{Exp}~2$	Lab-Applied	No	Incidental	Adult	48-hr	28	Yes
Wulf et al.	$2018,\mathrm{Exp}\ 2$	Lab-Applied	No	Observation	Adult	48-hr	28	Yes
Wulf et al.	$2018,\mathrm{Exp}\ 2$	Lab-Applied	No	Two	Adult	48-hr	42	Yes
Wulf et al.	2005	Applied	No	Observation	Adult	>48-hr	26	Yes

Note. KR = Knowledge of results; KP = Knowledge of performance.

The independent data extractions were compared and inconsistent results were highlighted. There was 89% absolute agreement between pairs of coders on 1344 data points. For those with disagreement, one of the researchers from the other coding pair reviewed the relevant experiment to confirm the value to be used in the analysis.<sup>3</sup>

Several articles failed to report the data necessary to calculate effect sizes at some or all time-points. A total of 39 authors were emailed with requests for missing data and 17 were able to provide data following a minimum one month period following the request. After requesting missing data, 25 experiments were excluded from primary analyses for missing retention data. A total of 52 effects from 51 experiments reported in 46 articles were included in the primary meta-analysis.

In addition to extracting effect sizes, inferential statistics were scraped from
published experiments that reported a statistically significant effect at retention. Two
authors (BM and JH) independently completed a *p*-curve disclosure form consisting of a
direct quote of the stated hypotheses for each experiment, the experimental design, and a
direct quote of the results indicating a significant result (see Appendix A). There was 94%
absolute agreement between the independent forms. Mismatches were resolved with
consensus.

#### 18 Outlier screening

The meta-analysis R package metafor (Viechtbauer, 2010) was used to screen the data for potentially influential outliers (see analysis script). In order to identify outlier values and exclude them from further analyses, the following nine influence statistics were

<sup>&</sup>lt;sup>3</sup> On one occasion, the third researcher was unable to match either effect calculation, so the involved researchers discussed the issue, determined the source of the inconsistency, and asked a fourth researcher to recalculate the effect size with clear instructions for avoiding confusion. The source of inconsistency was simply a rounding error when combining multiple groups and the fourth researcher was able to corroborate the calculation.

- calculated: a) externally standardized residuals, b) DFFITS values, c) Cook's distances, d)
- covariance ratios, e) DFBETAS values, f) the estimates of  $t^2$  when each study is removed in
- turn, g) the test statistics for (residual) heterogeneity when each study is removed in turn,
- 4 h) the diagonal elements of the hat matrix, and i) the weights (in %) given to the observed
- 5 outcomes during the model fitting. Any experiment with effects identified as extremely
- 6 influential by any three of the influence metrics were removed from subsequent analyses.

#### 7 Risk of bias

13

All articles were assessed for risk of bias by the lead author using the Cochrane Risk of Bias 1.0 tool (Julian PT Higgins et al., 2011). Each article was coded as either high risk, unclear (some concerns), or low risk on 7 dimensions: sequence generation, allocation concealment, incomplete outcome data, selective outcome reporting, blinding of outcome assessment, blinding of participants and personnel, and other sources of bias.

### Pre-specified analyses

#### Random effects model

A naïve random effects model was fit to the retention effect sizes to estimate the average reported effect of self-controlled learning and to assess heterogeneity in effect sizes between experiments. Heterogeneity was evaluated with the Q statistic and described with  $I^2$ . A mixed-effects model was fit to evaluate whether differences in experimental design or sample characteristics moderated the effect of self-controlled learning.

#### 20 Moderator analyses

Moderators were determined based on the authors' collective knowledge of the self-controlled learning literature. We coded for discrete differences in protocols between experiments to investigate whether differing methodologies resulted in different effect size

estimates. Further, based on a meta-analysis reporting that the effect of choice on intrinsic motivation can be moderated by whether participants were compensated for completing the study (Patall, Cooper, & Robinson, 2008), we also coded for compensation type. Finally, we investigated whether publication status was a moderator of the effect of self-control as part of our overall approach to examining the impact of publication bias on the self-controlled learning literature. The following six moderators were analyzed separately in mixed-effects models: a) Choice-type: Choices were categorized as either instructionally-irrelevant, knowledge of results, knowledge of performance, concurrent feedback, amount of practice, use of assistive device, practice schedule, observational practice, or difficulty of practice; b) Experimental setting: Experiments were categorized as 10 either laboratory, applied, or laboratory-applied. We defined a laboratory setting as one 11 where learners are asked to acquire a skill not typically performed in everyday life. We defined an applied setting as one where learners are asked to acquire a skill often 13 performed outside of a laboratory. Finally, we defined a laboratory-applied setting as one where learners are asked to acquire a skill resembling skills often performed outside the 15 laboratory but with researcher-contrived differences; c) Sub-population: The following subgroups were analyzed: Adult (18-50 years of age), children/adolescents (under 18-years old), older adult (over 50-years-old), and clinical (clinical population defined by the 18 research article); d) Publication status: Articles were classified as published or unpublished 19 (e.g., theses); e) Compensation: Whether participants were compensated for participating 20 in the experiment was categorized as compensated, not compensated, or not stated; f) 21

# 23 Adjusting for selection effects

22

Selection bias in the motor learning literature is likely caused by filtering based on the statistical significance of results (Lohse, Buchanan, & Miller, 2016). To assess and adjust for selection effects, the R package weightr (K. M. Coburn & Vevea, 2017) was used

Retention delay-interval: Coded as 24-hour, 48-hours, or >48-hours.

- to fit a Vevea-Hedges weight function model to the retention data (Vevea & Hedges, 1995).
- The weight-function model estimates the true average effect, heterogeneity, and the
- 3 probability that a non-significant result survives censorship and is available for analysis.
- 4 Selection effects are modelled by a step function that divides the effects into two bins at
- one-tailed p = .025, coinciding with a two-tailed p-value of .05. The probability of a
- 6 non-significant effect surviving censorship to appear in the model is estimated relative to
- <sup>7</sup> the probability of observing a study with a significant effect. The selection-adjusted model
- was compared to the naïve random effects model with a likelihood ratio test. Better fit
- 9 from an adjusted model suggests selection bias in the literature.

The adjusted estimate from the weight-function model was pre-registered as the
primary estimate of the true average effect in this meta-analysis. Please note that while
the weight-function model attempts to estimate the true effect of self-controlled learning
after correcting for selection biases, the estimated effect cannot be considered definitive.

Nevertheless, the adjusted estimate is likely less biased than the naïve random effects
estimate (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019; Hong & Reed, 2021;
Kvarven, Strømland, & Johannesson, 2020; Vevea & Hedges, 1995). The difference between
the estimates can be informative about the potential impact of selection biases, with larger
disparities between models suggesting greater selection effects.

### $_{19}$ P-curve analysis

To investigate the evidential value of the self-controlled learning literature, the
significant positive results at retention reported in peer-reviewed journals were submitted
to a p-curve analysis (Simonsohn, Simmons, & Nelson, 2015). To be included in the
analysis, articles needed to meet the following criteria: a) be a published article; b) state
explicitly that self-controlled learning was expected to be more effective than yoked
practice; c) report inferential statistics comparing a self-control group and a yoked group
directly on a retention test; d) conclude that the self-control group performed significantly

- better than the yoked group. If the article included multiple dependent measures showing a
- significant effect, the dependent measure priority list was used to select the highest priority
- measure. If only one measure was reported as significant, that effect was included even if
- the experiment included higher priority measures that were null. This resulted in a slightly
- different sample of effects from the random effects and weight-function models.
- The distribution of significant p-values is a function of the power of the experiments included in the analysis. If a p-curve included only Type 1 errors, the expected distribution would be uniform. As the power of included experiments increases, so too does the amount of right skew in the p-curve, with smaller p-values appearing more frequently than large p-values. The p-curve analysis tests the null hypothesis that there is no evidentiary value by analyzing the amount of right skew in the distribution of p-values. Conversely, if 11 researchers peek at their data and stop collecting when they reach statistical significance, a 12 practice known as p-hacking, the distribution of significant p-values under the null would 13 be left skewed, with p-values near .05 occurring more frequently. Varying mixtures of true 14 effect sizes and intensities of p-hacking produce varying shapes of p-curve, therefore the 15 observed p-curve was compared to the distribution of p-values expected if the studies were 16 conducted with 33% power. It is unlikely that researchers would continuously conduct 17 experiments that fail >66\% of the time whilst studying the self-controlled learning 18 phenomenon. Observing a p-curve significantly "flatter" than what would be expected 19 with 33% power would suggest a lack of evidential value among the significant results (Simonsohn, Nelson, & Simmons, 2014b, 2014a).

# Sensitivity analyses

21

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The primary analyses were followed up with several sensitivity analyses. Sensitivity 23 analyses are used to evaluate the sensitivity of the results to the specific parameters chosen for the original analyses. The self-controlled learning literature, like many areas of behavioural research, was not produced exclusively by registered experiments with

- pre-specified analysis plans and 100% reporting frequency. The complexity of selection
- <sup>2</sup> effects at various levels, including editorial decisions, author decisions, analysis decisions,
- and missing data, renders the accuracy of modeled effects impossible to estimate (E. C.
- <sup>4</sup> Carter, Schönbrodt, Gervais, & Hilgard, 2019). Producing a range of estimates based on
- 5 varying assumptions is intended to provide the reader with a broader picture of the
- 6 uncertainty of the point estimates in the primary analyses.
- Bias correction methods vary in their performance depending on the total amount of heterogeneity, the true average effect size, the amount of publication bias, and the intensity of p-hacking in the data (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019). To determine which bias correction models perform well in the various plausible conditions for data in this meta-analysis, model performance checks were conducted using the 11 Meta-Showdown Explorer shiny app developed by Carter and colleagues (2019). Simulated 12 conditions were as follows: Medium publications bias (significant results published at 100% 13 frequency, non-significant published at 20% frequency, wrong direction effects published at 14 5% frequency), medium questionable research practice environment (QRP; see Carter et al. 15 (2019) for detailed explanation of QRP environment),  $\tau=0, .2; g=0, .2, .5; k=60, good$ 16 performance defined as a maximum of .1 upward or downward bias, and maximum mean 17 absolute error of .1, also tested with maximum bias and error values of .15. With good 18 performance defined by a maximum bias in either direction of .1 and maximum absolute 19 error of .1, the weight function model and, to a lesser extent, p-curve models provided 20 coverage across all plausible conditions except the highest heterogeneity condition ( $\tau = .4$ ). 21 With good performance defined as a maximum bias and error of .15, the precision-effect 22 with standard error (PEESE) method provided good performance in all conditions. 23 Therefore, sensitivity analyses were conducted on effect size data via p-curve and PEESE methods. An additional sensitivity analysis of the estimated power among included studies was conducted with the z-curve (Bartoš & Schimmack, 2020). Z-curve, like p-curve, analyzes only statistically significant results and estimates the power of the included

- studies (called expected replication rate, ERR). However, unlike p-curve, z-curve is robust
- 2 to heterogeneity because it fits a finite mixture model of seven distributions, allowing the
- underlying true effects to vary. Further, z-curve also estimates the power of all studies that
- have been conducted (called expected discovery rate, EDR) which can be compared to the
- 5 observed discovery rate in order to test for the presence of publication bias.

### 6 Primary p-curve

A leave-one-out analysis of *p*-curve results was conducted to assess the extent to
which the primary results depended on the inclusion of one or two extreme results. Results
that depend on the inclusion of one or two extreme results should not be considered robust.

10 Results

#### 11 Risk of bias

The risk of bias assessment revealed lackluster reporting standards were pervasive 12 among the included articles (see Figure 2). For example, comparing a self-control group to 13 a yoked group usually involves first collecting a self-control participant, then their yoked counterpart. Despite this, most articles simply reported that the participants were randomly assigned to these conditions, with no indication of how this temporal constraint 16 was addressed. A similar issue was observed with respect to addressing outliers and 17 attrition. Over 75% of the included articles failed to mention outliers and how they were addressed (captured by the incomplete outcome data dimension). Most studies included in this study were not double-blind, largely due to the inherent difficulties in conducting a double-blind study of self-controlled motor learning. While the risk of bias associated with 21 a lack of double blinding has been debated (see Howick, 2008), it is nonetheless notable 22 that double-blinding was rare among the included studies.

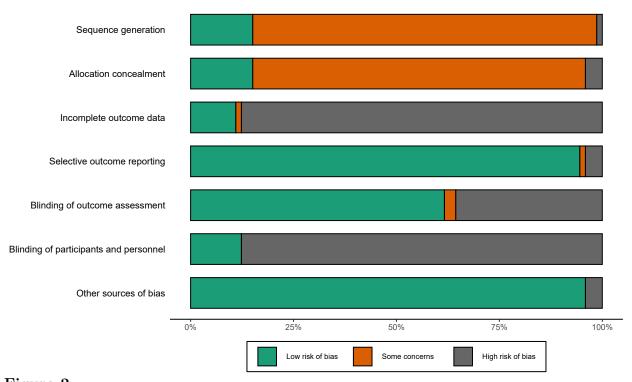


Figure 2

Proportion of studies with low risk, some concerns, and high risk of bias in each of the seven dimensions of the Cochrane RoB 1.0 tool.

## Outlier removal

- Two studies were flagged as significantly influential outliers by all nine influence
- metrics calculated during data screening: Lemos, Wulf, Lewthwaite, and Chiviacowsky
- $_{4}~~(2017),\;g=3.7,\;\mathrm{and}$  Marques, Thon, Espanhol, Tani, and Corrêa (2017), g=3.95. No
- 5 other effect sizes were identified as outliers by any metric. Both outliers were removed from
- 6 all subsequent analyses.

#### 7 Naïve random effects model

- The naïve random effects model estimated the average treatment effect of
- self-controlled practice, g=.44 ( $k=52,\ N=2061,\ 95\%\ CI\ [.31,\ .56]$ ). However, there was
- significant variability in the average effect estimated across experiments, Q(df = 51) =

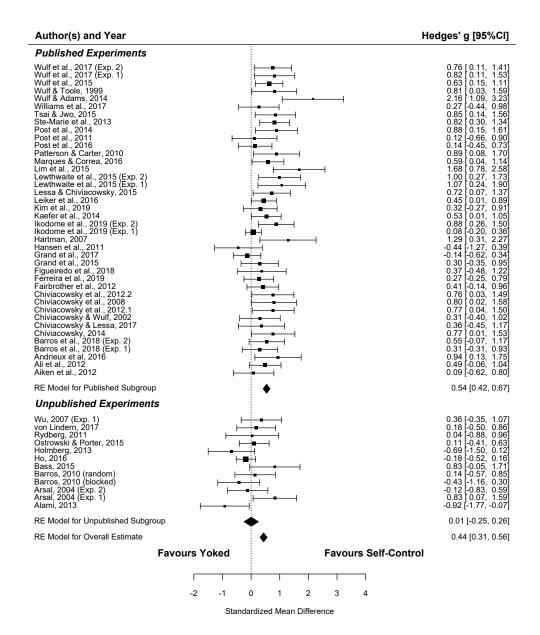


Figure 3

Forest plot of Hedges' g (95% CI) for self-controlled versus yoked groups on retention tests. Size of squares is proportional to  $1/\sigma^2$  (precision). Experiments are divided into published and unpublished subgroups and the black polygons represent 95% CI estimates from subgroup analyses. The black polygon at the bottom of the figure represents the 95% CI estimate for all included experiments.

- 103.45, p < .0001,  $\tau = .31$ . It was estimated that 47.9% ( $I^2$ ) of the total variability in
- effect sizes across experiments was due to true heterogeneity in the underlying effects
- measured (see Figure 3).

### Moderator analyses

Six moderators selected for theoretical and/or methodological reasons were tested 5 separately. Five moderators failed to account for a significant amount of heterogeneity: experimental setting  $(p = .46, R^2 = 1\%)$ , compensation  $(p = .99, R^2 = 0\%)$ , choice-type  $(p = .99, R^2 = .9\%)$ = .71,  $R^2 = 0\%$ ), sub-population (p = .74,  $R^2 = 0\%$ ), and retention interval (p = .54,  $R^2$ = 0%). One moderator, publication status, accounted for a statistically significant amount of heterogeneity, p < .0001,  $R^2 = 48\%$ . Among published experiments, self-controlled practice had a strong benefit, g = .54, 95% CI [.28, .81]. However, among unpublished 11 experiments, self-controlled practice had essentially no effect, g = .003, 95% CI [-.23, 24].

#### Selection model

12

The weight-function model combines an effect size model and a selection model 14 (Hedges & Vevea, 1996). The effect size model is equivalent to the naïve random effects 15 model, specifying what the distribution of effect sizes would be in the absence of 16 publication bias or other selection effects. The selection model accounts for the probability 17 a given study survives selection based on its p-value and specifies how the effect size distribution is modified by selection. A weight-function model with a p-value cutpoint of (one-tailed) .025 was fit to the retention effect size estimates (see Figure 4). The results of a likelihood ratio test suggest the adjusted model was a significantly better fit to the data than the unadjusted model,  $\chi^2(df=1)=21.18, p<.0001.^4$  The adjusted effect size

 $<sup>^4</sup>$  Be aware that the likelihood ratio test is not robust to misspecification of the random effects model (Hedges & Vevea, 1996).

- estimate was significantly different from zero, g = .107, p < .001, 95% CI [.05, .17].
- <sup>2</sup> According to the adjusted model, non-significant results were 6% as likely to survive
- selection as significant results. Note that the weightr function failed to estimate the
- 4 random effects model and the results reported here are based on a fixed-effect estimate.

## 5 P-curve

The purpose of the p-curve analysis was to investigate the evidential value in the published reports (N=26) of statistically significant self-controlled learning benefits. Visual inspection of Figure 4 reveals a v-shaped distribution with the greatest frequency of p-values in the <.05 bin. The observed p-curve was significantly flatter than would be expected if the experiments had 33% power, p=.0035, indicating an absence of evidential value. Conversely, the half p-curve (Simonsohn, Simmons, & Nelson, 2015) was significantly right skewed, suggesting the presence of evidential value. Sensitivity analysis, however, revealed that the half curve does not remain significantly right skewed following removal of the most extreme p-value from the sample. The estimated power of the included studies was 5%, 95% CI [5%, 17%].

#### 16 Interim discussion

The primary results described above suggest that selection effects have caused a seriously distorted record of self-controlled learning. Estimated benefits are less than one third of the naïve estimate, g = .107, 95% CI [.05, .17]. The p-curve analysis failed to detect robust evidence of a self-controlled learning effect. The performance of the weight-function model depends on the specific conditions present in the meta-analysis, although these conditions are unknowable (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019). It was necessary to conduct sensitivity analyses with additional bias correction methods to assess the reliability of the selection-adjusted weight-function model estimate. Based on performance checks conducted under a range of plausible conditions, it was

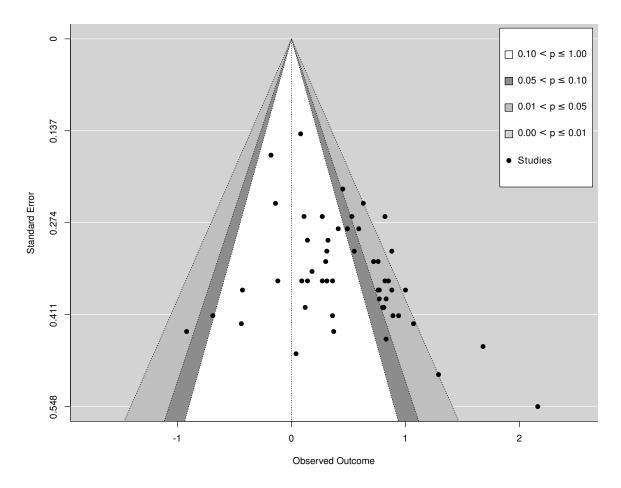


Figure 4

Funnel plot of self-controlled learning studies at retention. Standard error is plotted on the y-axis and Hedges' g is plotted on the x-axis. Dark gray contour regions represent two-tailed p-values between .10 and .05 (not quite significant). The light gray contour regions represent two-tailed p-values between .05 and .01. In the absence of bias (and other forms of heterogeneity), the most precise experiments would center on the naïve random effects estimate near the top of the plot and as experiments get progressively less precise they would move down the plot and spread out symmetrically. In the presence of bias, one would expect experiments to cluster in the light gray contour regions. The clustering of experiments in the positive light gray contour region in the above plot suggests substantial bias.

- determined that sensitivity analyses conducted with a PEESE meta-regression and p-curve
- <sup>2</sup> effect size estimation would provide good performance coverage across most plausible
- 3 conditions.

4

### Sensitivity analyses

### 5 Precision-effect with standard error (PEESE) model

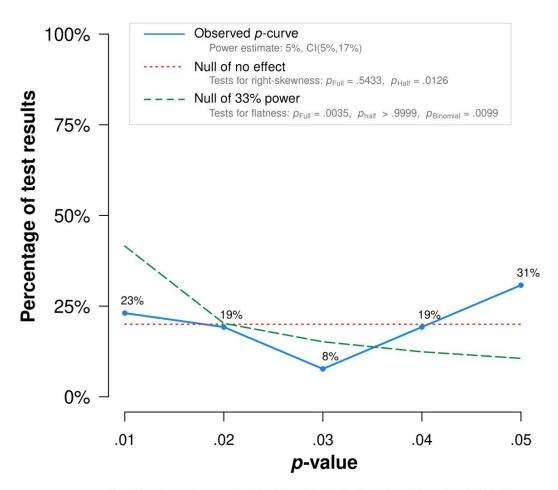
- When publication bias is present in a body of evidence, sample size and effect size
- $_{7}\,$  can be negatively correlated (Stanley & Doucouliagos, 2014). The PEESE model fits a
- 8 quadratic relationship between effect size and standard error to reflect the intuition that
- 9 publication bias is stronger for low precision studies than high precision studies. The
- 10 rationale is that low precision studies need to overestimate effects to achieve significance
- and get published, while high precision studies can publish without exaggerated effects;
- thus, creating greater publication bias among lower precision studies (E. C. Carter,
- Schönbrodt, Gervais, & Hilgard, 2019; Stanley & Doucouliagos, 2014). A
- weighted-least-squares regression model was fit with effect size regressed on the square of
- the standard error, weighted by the inverse of the variance:

$$g_i = b_0 + b_1 s e_i^2 + e_i$$

- 16 The PEESE method estimated a non-significant benefit of self-controlled learning after
- controlling for publication bias, g = .054, 95% CI [-.18, .29], p = .659.

# <sup>18</sup> *P*-curve effect estimation

- A p-curve model was fit to the overall retention effect size data, unlike the first
- <sup>20</sup> primary p-curve which was fit to the reported significant results. The p-curve is a function
- of sample size and effect size, and because sample size is known, the effect size that
- provides the best fit to the observed p-curve can be estimated (Simonsohn, Nelson, &



Note: The observed p-curve includes 26 statistically significant (p < .05) results, of which 12 are p < .025. There were no non-significant results entered.

Figure 5

P-curve analysis of published experiments that were statistically significant at retention. If the included experiments are studying a true null hypothesis the expected distribution of p-values is uniform, represented by the dotted line. If the experiments are studying a true effect, the expected distribution becomes increasingly right skewed as a function of statistical power. The expected right skewed distribution associated with 33% power is plotted by the dashed line. The observed p-curve is plotted by the solid line and was substantially flatter than the 33% power distribution. The half p-curve analysis included p-values below p = .025 and was significantly right skewed. The right skew did not survive deletion of the most extreme value.

- Simmons, 2014b). A p-curve analysis conducted with the package dmetar (Harrer,
- <sup>2</sup> Cuijpers, Furukawa, & Ebert, 2019) was used to estimate the average effect size among the
- statistically significant effects in the meta-analysis. The model estimated an average effect
- of g = .035. The estimated power of included studies was 7%, 95% CI [5%, 22%].
- <sup>5</sup> Unfortunately, p-curve does not perform well in the presence of heterogeneity and these
- 6 results should be interpreted cautiously.

# Z-curve

A z-curve was fit to the overall retention data and estimated the power of statistically significant studies (ERR) as 12%, 95% CI [3%, 34%]. The power of all studies conducted (EDR) was estimated as 6%, 95% CI [5%, 13%]. The 95% confidence intervals for both the ERR and EDR failed to include the observed discovery rate of 48%, suggesting significant publication bias in the data.

### 13 Acquisition and transfer

In light of the evidence that experiments are apparently selected for positive self-controlled learning effects at retention, pre-planned exploratory estimates of the effect of self-controlled practice on acquisition and transfer performance can no longer be considered reliable. However, given that some have argued that transfer tests are more sensitive measures of motor learning than delayed retention tests (Chiviacowsky & Wulf, 2002; Fairbrother, Laughlin, & Nguyen, 2012), the transfer test data were analyzed via both naïve random effects and weight function models. The naïve estimate at transfer was g = .52, while the bias corrected estimate was g = .17, p = .24. As with delayed retention, the selection model provided a better fit to the transfer data than the naïve model, p = .008. The primary take away from these analyses is that the reported self-controlled

learning effects to date are unreliable.

a suite of sensitivity analyses.

16

2 Discussion

The primary objective of this meta-analysis was to assess the effect of providing
choices during the acquisition of a motor skill on delayed retention performance in the
general population. A secondary objective was to test between motivation and
informational explanations for self-controlled learning benefits by investigating whether
choice-type moderates the effect of choice. To this aim, an extensive search for experiments
that compared self-controlled practice to a yoked comparison group was conducted. Effect
size and moderator data were ascertained from data reported in the research articles or, in
some cases, received directly from the authors of the studies. Efforts were taken to ensure
that each effect size calculation and moderator code could be reproduced by an
independent party. In parallel, the results of published experiments that achieved a
hypothesized statistically significant result in favour of self-control were extracted directly
from the articles and outlined in a p-curve disclosure form (see Appendix A).

Pre-registered primary analyses were applied to the data and results were followed up with

The naïve random effects model estimated a benefit from self-controlled practice of g = .44. However, the naïve model fails to account for selection effects, such as publication bias and p-hacking, and as such overestimates the true average effect when these selection effects are present (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019; Hedges & Vevea, 1996; Stanley & Doucouliagos, 2014). Publication status was a significant moderator of the self-controlled practice effect, accounting for 48% of the total heterogeneity in the model. Published experiments reported an average benefit of g = .54 while unpublished experiments reported no benefit at all on average. It is possible that researchers use statistical significance, typically defined as p < .05 on a two-tailed test, to filter their results for publication. To account for potential selection effects driven by statistical

- significance, a weight-function model was fit to the retention test effect size data with a one-tailed p-value cutpoint of .025 included in the model (Vevea & Hedges, 1995). The adjusted model provided a significantly better fit to the data than the naïve random effects model. The model estimated the selection-adjusted benefit of self-controlled learning as q = .11, a dramatic departure from the naïve estimate of g = .44. Two additional bias correction techniques were conducted to assess the sensitivity of this result to changes in correction methodology. The PEESE method estimated the effect at q = .05, while p-curve estimated g = .04, and neither analysis was able to rule out the null hypothesis. In parallel to the meta-analysis described above, a p-curve was conducted on the reported significant results. The p-curve used somewhat different inclusion criteria focusing 10 only on published, statistically significant results suggesting a self-controlled learning 11 benefit. In addition, the p-curve included results reported for any dependent measure in an 12 article, even if the focal measure (of this meta-analysis) was reported as non-significant. 13 Therefore, the p-curve was more inclusive of evidence reported by authors as favouring a 14 self-controlled benefit while ignoring experiments with null effects. The results revealed 15 both significant right skew below p = .025 (two-tailed) and a p-curve that was significantly 16 flatter than a distribution with an expected power of 33%. The evidence of right skew, 17 indicating superiority of self-control relative to voked conditions, was tenuous and did not 18 survive the deletion of the most extreme result—an experiment that reported a benefit from 19
- It appears from these analyses that the substantial self-controlled learning literature is, as of now, insufficient to provide evidence that self-controlled practice is more effective than a yoked practice. The bias correction techniques applied in this analysis are sensitive to unknown conditions, such as the true average effect size and the amount of true heterogeneity; although efforts were taken to provide coverage across most plausible

self-control of g = 2.16 (Gabriele Wulf & Adams, 2014). The overall p-curve produced an

estimate that the true power of the included experiments was 5%, leading to a rejection of

the hypothesis that the experiments contained evidential value.

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- conditions. The corrected estimates produced by the weight-function model, p-curve, and
- <sup>2</sup> PEESE methods appeared to converge on trivially small effects. Further, the *p*-curve of
- 3 significant results suggested a lack of evidential value. Based on the model performance
- 4 parameters we tested (E. C. Carter, Schönbrodt, Gervais, & Hilgard, 2019), which allowed
- 5 up to .15 units of maximum bias or mean absolute error as acceptable performance, our
- results are consistent with a self-controlled learning benefit ranging from g = -.11 to .26,
- with a plausible upper 95% confidence limit of g = .33. Thus, this analysis does not rule
- 8 out the possibility that self-controlled practice provides meaningful motor learning benefits
- on average. The present literature, however, appears insufficient to establish that a
- 10 self-control benefit indeed exists.
- Turning to the current theoretical debates surrounding the motivational and informational underpinnings of self-controlled learning, these debates now seem moot, or at least premature. The effectiveness of self-control was not moderated by choice-type, suggesting that self-controlled practice may be ineffective regardless of the nature of the choices provided. Indeed, the only factor we tested that moderated the effect of self-controlled practice was publication status.

#### 7 Future studies

Given that the current meta-analysis failed to support the widely touted assertion
of a substantial self-controlled learning benefit (Sanli, Patterson, Bray, & Lee, 2013;
Ste-Marie, Carter, & Yantha, 2019; Gabriele Wulf & Lewthwaite, 2016), considerations
need to be given to the design and research practices for future studies. Registered reports
provide one possible path forward (Caldwell et al., 2020). A registered report involves
submitting a research proposal to a two-phase peer-review. The first phase of the review
occurs prior to data-collection and is assessed based on the proposed methodology,
rationale, and potential contribution. If accepted in principle, researchers commit to
carrying out the registered experiment and submitting the results in a final article for the

- second phase of peer-review. The final article is peer-reviewed for quality and adherence to
- the registered plan, but accept-reject decisions at this point are not based on the results.
- In theory, this practice should eliminate p-hacking and, for literatures composed entirely of
- 4 registered reports, publication bias. A number of motor behaviour and/or kinesiology
- 5 journals have begun adopting registered reports as an option for authors, including the
- 6 Human Movement Science, Frontiers in Movement Science and Sport Psychology, Journal
- of Sport and Exercise Psychology, Journal of Sport Sciences, and Reports in Sport and
- 8 Exercise (formerly Registered Reports in Kinesiology).
- While registered reports are a potentially fruitful process to begin the accumulation 9 of evidence regarding self-controlled learning, there are practical issues with investigating 10 self-controlled learning that motor learning researchers may find overly burdensome. For 11 example, to have 80\% power to detect an effect of g = .26 with a two cell experimental 12 design, 506 participants are required. If the weight-function adjusted estimate of q = .11 is 13 accurate, N = 2600 are required. More challenging still would be testing between 14 hypothesized motivational and informational mechanisms. For example, if a 2 (choice) X 2 15 (choice-relevance) experiment were conducted to test whether the instructional-relevance of 16 choice fully attenuates its effect, four times as many participants would be required to 17 maintain the same degree of power (Simonsohn, 2015). In contrast, the median sample size 18 among experiments included in this meta-analysis was N=36, which is typical of motor 19 learning experiments in general (Lohse, Buchanan, & Miller, 2016). 20
- In addition to challenges with establishing that an effect exists, additional challenges will emerge if researchers are interested in generalizing the benefits of self-controlled practice beyond comparisons to a yoked group, as has been the case thus far (Ste-Marie, Carter, & Yantha, 2019; Gabriele Wulf & Lewthwaite, 2016). Yoking may allow for inferences to be made about the act of making certain choices, but it may not provide an adequate control group for evaluating best practices in an applied setting (e.g., J. A. C. Barros, Yantha, Carter, Hussien, & Ste-Marie, 2019; Ste-Marie, Carter, & Yantha,

- <sup>1</sup> 2019; Yantha, 2019). Indeed, given that our estimate suggests the advantage of
- <sup>2</sup> self-controlled over yoked practice is small, if it exists at all, it seems unlikely that
- 3 self-control would be more effective than an instructor-guided practice. An
- 4 instructor-guided group could easily be argued to have advantages over a yoked group,
- because of the ability for the instructor to adapt choices to the current practice context
- and to make use of personal experience and expertise. Following this logic, experiments
- 7 investigating the benefit of self-controlled over instructor-guided practice could conceivably
- 8 require substantially larger samples than experiments that use yoked comparison groups.

# Exploratory analysis of pre-registered experiments

There have been, to our knowledge, four pre-registered experiments that have 10 compared self-controlled and yoked practice (Grand, Daou, Lohse, & Miller, 2017; McKay 11 & Ste-Marie, 2020; St. Germain et al., 2021; Yantha, 2019). Three of these experiments 12 failed to meet our inclusion criteria because they were not published or part of an accepted 13 thesis at the time of the analysis (McKay & Ste-Marie, 2020; St. Germain et al., 2021; Yantha, 2019). These pre-registered experiments should provide estimates of the 15 self-control effect unbiased by selection effects and are therefore more useful for estimating the real average effect than attempting to correct biased experiments after the fact (E. C. 17 Carter, Schönbrodt, Gervais, & Hilgard, 2019). A random effects model was used to estimate the average effect of self-control in the four experiments and yielded q = .02, 95%19 CI [-.17, .21]. These results converge with the bias-corrected estimates around trivially small differences between self-controlled and yoked practice conditions.

#### 2 Conclusion

We set out to assess the effect of self-controlled practice on motor learning. The
published literature on the subject to date appeared unambiguously supportive of a
self-control benefit, yet the results of this meta-analysis suggest this may not be the case.

- If authors, reviewers, and editors select for statistical significance when deciding if
- 2 experiments get published, the published literature becomes biased (Ioannidis, 2005).
- <sup>3</sup> Worse still, filtering based on statistical significance may well incentivize researchers to
- 4 leverage researcher degrees of freedom to achieve a significant result, a practice known as
- <sup>5</sup> p-hacking, further biasing the literature (Wicherts et al., 2016). An instructive example of
- 6 the potential impact of selection effects comes from research studying the so-called
- <sup>7</sup> ego-depletion effect (Roy F. Baumeister, Vohs, & Tice, 2007; Hagger, Wood, Stiff, &
- 8 Chatzisarantis, 2010). In a typical study, participants are asked to engage in activities that
- 9 supposedly drain a limited reservoir of willpower, termed ego-depletion, and are
- subsequently measured on a dependent measure requiring an additional exertion of
- self-control, such as a Stroop task. The typical finding is that performance suffers on the
- second task if ego-depletion occurs beforehand. A meta-analysis by Hagger and colleagues
- (2010) reported the average effect of ego-depleting interventions on willpower dependent
- measures was d = .62. There was apparent consensus in the field that willpower relied on a
- limited resource due to the ostensibly unambiguous evidence in support of the theory (R.
- <sup>16</sup> F. Baumeister & Vohs, 2016). Nevertheless, when bias correction methods were applied in
- <sup>17</sup> a meta-analysis of ego-depletion literature, the adjusted estimates often did not differ
- significantly from zero (E. C. Carter, Kofler, Forster, & McCullough, 2015). Subsequently,
- a pre-registered, multi-lab replication project tested a sample of N=2141 and reported
- that the ego-depletion effect was close to zero (Hagger et al., 2016). Thus, a prominent
- 21 psychological construct substantiated by a large corpus of peer-reviewed evidence was
- 22 investigated using cutting edge meta-analytic techniques that corrected for selection bias
- 23 and the result was a trivially small estimated effect—an estimate supported by a subsequent
- 24 large scale pre-registered replication effort. Notably, both the bias corrected meta-analysis
- 25 and the subsequent multi-lab replication efforts have been criticized by ego-depletion
- theorists (R. F. Baumeister & Vohs, 2016; Cunningham & Baumeister, 2016). Others have
- 27 sharply challenged these critiques (Schimmack, 2020), and while debate continues among

- social psychologists about the underlying theory at stake (e.g., Dang, 2018), there is
- 2 consensus that several methods shown to produce positive results in the past are unlikely
- 3 to replicate in future experiments.
- In stark parallel to the ego-depletion literature, the findings of the current research
- 5 suggest the self-controlled motor learning literature may be similarly biased. As motor
- 6 learning researchers consider the path forward for self-controlled learning, non-bias related
- <sup>7</sup> limitations of the extant literature should be addressed. For example, yoked groups fail to
- s isolate putative motivational and informational processes when self-controlling learners
- 9 make choices pertinent to acquiring a skill (M. J. Carter, Rathwell, & Ste-Marie, 2016; M.
- J. Carter & Ste-Marie, 2017b; Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015). Further,
- exclusive reliance on yoked comparison groups limits the generalizability of self-controlled
- learning to applied settings where the alternative to self-control is typically coach or
- instructor control (i.e., those with domain-specific knowledge). As motor learning
- 14 researchers in this area move forward, they are faced with the question of whether this
- 15 effect is worth the resources required to study it. If that answer is yes, then in addition to
- being pre-registered and an adequately powered design, future self-controlled learning
- 17 experiments should provide insight about either the underlying processes at work or the
- 18 real world usefulness of this practice variable.

#### 19 Contributions

- 20 Contributed to conception and design: BM, JH, ZY, MJC, DSM.
- 21 Contributed to acquisition of data: BM, JH, ZY, MJC.
- 22 Contributed to analysis and interpretation of data: BM.
- 23 Contributed to drafting and revisions of article: BM, JH, ZY, MJC, DSM.

#### Acknowledgments

We would like to thank Heather Smith for her help with data extraction.

### Data, materials, and code availability

- All material, data, and scripts to reproduce our analyses and figures can be accessed
- 5 here: https://osf.io/qbg69.

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#### R packages used in this project

- R (Version 4.0.4; R Core Team, 2021) and the R-packages computees (Re, 2013),
- 8 dmetar (Version 0.0.9000; Harrer, Cuijpers, Furukawa, & Ebert, 2019), kableExtra (Version
- 9 1.3.4; Zhu, 2021), meta (Balduzzi, Rücker, & Schwarzer, 2019; Version 4.18.0; Harrer,
- Cuijpers, Furukawa, & Ebert, 2019; Viechtbauer, 2010), metafor (Version 3.0.2;
- Viechtbauer, 2010), papaja (Version 0.1.0.9997; Aust & Barth, 2020), rcolorbrewer
- (Neuwirth, 2014), robvis (Version 0.3.0; McGuinness, 2019), tidyverse (Version 1.3.0;
- Wickham et al., 2019), and weightr (Version 2.0.2; Kathleen M. Coburn & Vevea, 2019).

#### Conflict of interest

The authors declare no competing interests.

## Funding

- BM was supported by a Social Sciences and Humanities Research Council (SSHRC)
- 18 CGS-Doctoral Grant. MJC was supported by a Natural Sciences and Engineering Research
- <sup>19</sup> Council (NSERC) of Canada Discovery Grant (RGPIN-2018-05589).

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# Appendix A

*P*-curve disclosure form

Table A1

Experiment information from papers included in the p-curve analysis.

Original paper	Quoted text from original paper indicated predicted benefit of self-control relative to yoked practice	Design	Key statistical result	Quoted text from original paper with statistical results	Result
Andrieux,	"Thus, we hypothesized that a	Two cell	Difference in	"A follow up analysis restricted to the	F(1, 36)
Danna &	practice condition in which the		means	first two blocks revealed a significant	= 4.85
Thon (2012)	learner could set the level of task			difference between groups, $F(1, 36) =$	
	difficulty would be more beneficial for			4.85, p $< .05$ , partial eta squared $= .12$ .	
	learning than a condition in which			Self-controlled learners were significantly	
	this parameter was imposed."			more accurate (M AE = $12.73$ mm, SE	
				= 1.57) than their yoked counterparts	
				(M AE = 18.1 mm, SE = 1.87) after a	
				24-hr rest."	
Andrieux,	"Two main reasons led us to expect	Four cell (Full	Difference in	"Planned pairwise comparisons revealed	F(1, 44)
Boutin, &	that self-control of nominal task	self-control, full	means	that the self-control groups exhibited	= 14.02
Thon (2016)	difficulty would enhance motor skill	yoked, self-control		lower RMSE (SC $+$ SC, SC $+$ YO, and	
	learning, and especially when	then yoked, yoked		YO + SC groups) than their yoked	
	introduced during early practice	then self-control)		group counterparts (YO $+$ YO group),	
	rather than during late practice."			F(1, 44) = 14.02, p < .01."	

Brydges,	"We hypothesised that participants	2 (Control: self,	Difference in	"The self-process group performed better	F(1,23) =
Carnahan,	with self-guided access to instruction	yoked) X 2 (Goals:	means	on the retention test than the	4.33
Safir &	would learn more than participants	process, outcome)		control-process group (Fig. 1). This	
Dubrowski	whose access to instruction was			effect was significant for time taken,	
(2009)	externally controlled."			(F[1,23] = 4.33, P < 0.05)."	
Chiviacowsky	"We hypothesized that participants	Two cell	Difference in	"The Self group outperformed the Yoked	t(26) =
(2014)	of the self-controlled group would		means	group. The group main effect was	2.08
	show superior motor learning than			significant, t(26) = 2.08, p = .04, d =	
	yoked participants"			.78."	
Chiviacowsky,	"Therefore, the purpose of the	Two cell	Difference in	"The self-control group had higher	F(1, 24)
Wulf, de	present study was to examine		means	accuracy scores than the yoked group.	= 4.40
Medeiros,	whether the learning benefits of			This difference was significant, $F(1, 24)$	
Kaefer &	self-controlled KR would generalize			= 4.40, p < .05."	
Tani (2008)	to children."				
Chiviacowsky,	"The potential benefits of	Two cell	Difference in	"The self-control group was overall more	F(1, 26)
Wulf,	self-controlled practice have yet to be		means	effective than the yoked group. Time in	= 4.25
Lewthwaite,	examined in persons with PDunder			balance was significantly longer for the	
& Campos	the assumption that self-controlled			self-control group, F(1, 26) = 4.25, p <	
(2012)	practice would enhance the learning			.05."	
	of the task"				

Chiviacowsky	"We predicted that self-controlled	Two cell	Difference in	"The day following practice, a retention	F(1, 28) =
Wulf,	practice, in particular the ability to		means	test (without feedback) revealed lower	4.72
Machado &	choose when to receive feedback,			AEs for the self-control group than the	
Rydberg	would result in more effective			yoked group (see Figure 2, right). The	
(2012)	learning compared to a practice			group difference was significant, with	
	condition without this opportunity			F(1, 28)=4.72, p < 0.05, eta squared	
	(yoked group)."			=.14."	
Hartman	"The primary aim of this study was	Two cell	Difference in	"To assess the relatively permanent or	F(1, 17)
(2007)	to test whether there would exist a		means	learning effects of practice with or	= 8.29
	learning advantage for a			without a self-controlled use of a balance	
	self-controlled group, as opposed to a			pole, both groups performed a retention	
	yoked control group, for learning a			test on Day 3. The group effect was	
	dynamic balance task."			significant, $F(1, 17) = 8.29, p < .01,$	
				with the Self-control group	
				outperforming the yoked group."	
Kaefer,	"both self-controlled groups	2 (Control: self,	Difference in	"The groups' main effects were detected	F(1, 52)
Chivia-	(introverts and extroverts) will	yoked) X 2	means	on the factor "feedback type":	= 4.13
cowsky,	achieve a level of activation that	(Personality:		Self-controlled groups performed better,	
Meira Jr. &	facilitates learning through the	introvert, extrovert)		F(1, 52) = 4.13, p < .05, compared with	
Tani (2014)	control of stimulation source			externally controlled groups"	
	(feedback) in comparison with the				
	groups that do not have control over				
	it."				

Leiker, Bruzi,	"We hypothesized that participants	Two cell	Difference in	"Controlling for pre-pest, there was a	F(1,57) =
Miller,	in the self-controlled group would		means	significant main effect of group, $F(1,57)$	4.51
Nelson,	show superior learning (i.e., better			= 4.51, p = 0.04, partial eta squared =	
Wegman &	performance on retention and			0.07, such that participants in the	
Lohse (2016)	transfer tests) compared to the yoked			self-controlled group performed better	
	group."			on the post-test than participants in the	
				yoked group."	
Lemos, Wulf,	"Independent of which factor the	Two cell	Difference in	"On the retention test, choice	F(1, 22)
Lewthwaite	learner is given control over e or		means	participants clearly outperformed the	= 88.16
&	whether or not this factor is directly			control group. The group main effect	
Chiviacowsky	related to the task to be learned e			was significant, $F(1,22)=88.16,p<$	
(2017)	the learning benefits appear to be			0.01."	
	very robust."				
Lessa &	"it was hypothesized that older	Two cell	Difference in	"The analysis of the retention test	F(1,34) =
Chiviacowsky	adult participants of the self-group		means	revealed significant differences between	4.87
(2015)	would demonstrate superior motor			groups, $F(1,34) = 4.87$ , $p < .05$ with	
	learning results, presenting faster			participants of the self-control group	
	task times on the speed cup-stacking			presenting faster task times compared to	
	task, when compared with			yoked participants."	
	participants in the yoked control				
	group."				

Lewthwaite,	"In the present experiment, the	Two cell	Difference in	"On the retention test, during which	F(1, 22)
Chivia-	choice learners were given was not		means	white golf balls were used, the choice	= 7.31
cowsky,	related to task performance per se.			group showed significantly higher	
Drews &	Therefore, any learning benefits			putting accuracy (36.8) than the yoked	
Wulf (2015;	resulting from having, as opposed to			group (26.4), $F(1, 22) = 7.31$ , $p < .05$ "	
Exp. 1)	not having, a choice would suggest				
	that motivational factors are				
	responsible for those effects."				
Lewthwaite,	"Given the potential theoretical	Two cell	Difference in	"On the retention test 1 day later, the	F(1, 27)
Chivia-	importance of the finding in		means	choice group demonstrated significantly	= 7.93
cowsky,	Experiment 1, we wanted to replicate			longer times in balance than the yoked	
Drews &	it with another task and different			group, $F(1, 27) = 7.93$ , $p < .01$ ."	
Wulf (2015;	type of choice."				
Exp. 2)					
Lim, Ali,	"It was expected that a self-controlled	Two cell	Difference in	"In the retention phase, there was a	F(1, 22)
Kim, Choi &	feedback schedule would be more		means	significant main effect for Group (F(1,	= 18.27
Radlo (2015)	effective for the learning and			(22) = 18.27, p < .05). The follow-up	
	performance of serial skills for both			test indicated that the Self-controlled	
	acquisition and retention phases than			feedback group had higher performance	
	a yoked schedule."			(Cohen's $d = 6.4$ ) than the	
				Yoked-feedback group during the	
				retention test in both blocks."	

Patterson,	"We expected that the structure of	2 (Control: self,	Difference in	"Specifically, the Self-Self condition	F(1, 18)
Carter &	this self-controlled practice context	yoked) X $3$	means	demonstrated less $ CE $ compared to	= 8.06
Sanli (2011:	would either add to or compromise	(Structure: full, all,		their Yoked-Yoked counterparts. This	
Comparison	the existing benefits attributed to a	faded)		main effect was significant, $F(1, 18) =$	
1)	self-controlled practice context."			8.06, p < .05."	
Patterson,	"We expected that the structure of	2 (Control: self,	Difference in	"The All-Self condition demonstrated	F(1, 18)
Carter &	this self-controlled practice context	yoked) X 3	means	less $ \mathrm{CE} $ compared to the All-Yoked	= 4.67
Sanli (2011:	would either add to or compromise	(Structure: full, all,		condition. This main effect was also	
Comparison	the existing benefits attributed to a	faded)		statistically significant, $F(1, 18) = 4.67$ ,	
2)	self-controlled practice context."			p < .05."	
Patterson,	"We expected that the structure of	2 (Control: self,	Difference in	"The Faded-Self condition demonstrated	F(1, 18)
Patterson, Carter &	"We expected that the structure of this self-controlled practice context	2 (Control: self, yoked) X 3	Difference in means	"The Faded-Self condition demonstrated less  CE  compared to the Faded-Yoked	F(1, 18) = 5.78
	-	•			, ,
Carter &	this self-controlled practice context	yoked) X 3		less  CE  compared to the Faded-Yoked	, ,
Carter & Sanli (2011:	this self-controlled practice context would either add to or compromise	yoked) X 3 (Structure: full, all,		less  CE  compared to the Faded-Yoked condition, supported by a main effect for	, ,
Carter & Sanli (2011: Comparison	this self-controlled practice context would either add to or compromise the existing benefits attributed to a	yoked) X 3 (Structure: full, all,		less  CE  compared to the Faded-Yoked condition, supported by a main effect for	, ,
Carter & Sanli (2011: Comparison 3)	this self-controlled practice context would either add to or compromise the existing benefits attributed to a self-controlled practice context."	yoked) X 3 (Structure: full, all, faded)	means	less  CE  compared to the Faded-Yoked condition, supported by a main effect for group, $F(1, 18) = 5.78, p < .05$ ."	= 5.78
Carter & Sanli (2011: Comparison 3) Post,	this self-controlled practice context would either add to or compromise the existing benefits attributed to a self-controlled practice context."  "It was hypothesized that learners in	yoked) X 3 (Structure: full, all, faded)	means  Difference in	less  CE  compared to the Faded-Yoked condition, supported by a main effect for group, F(1, 18) = 5.78, p < .05." "The univariate ANOVA for retention	= 5.78 $F(1, 29)$
Carter & Sanli (2011: Comparison 3) Post, Fairbrother,	this self-controlled practice context would either add to or compromise the existing benefits attributed to a self-controlled practice context."  "It was hypothesized that learners in the SC group would demonstrate	yoked) X 3 (Structure: full, all, faded)	means  Difference in	less  CE  compared to the Faded-Yoked condition, supported by a main effect for group, $F(1, 18) = 5.78$ , $p < .05$ ."  "The univariate ANOVA for retention revealed a significant group effect, $F(1, 18) = 1.00$	= 5.78 $F(1, 29)$

Ste-Marie,	"We hypothesized that the Learner	Two cell	Difference in	"A separate independent samples t-test	t(58) =
Vertes, Law	Controlled group would show		means	showed that the Learner Controlled	3.21
& Rymal	superior physical performance of the			group had significantly higher	
(2013)	trampoline skills compared to the			performance scores compared to the	
	Experimenter Controlled group."			Experimenter Controlled group at	
				retention, t(58) = 3.21, p < .05, d =	
				.753."	
Wulf &	"We asked whether giving performers	2(Group:	Difference in	"On the retention test the choice	F(1,18) =
Adams	an incidental choice would also result	${\it self-control, yoked})$	means	group showed fewer errors than the	25.35
(2014)	in more effective learning of exercise	X 3 (Exercise: toe		control group. The main effects of	
	routines."	touch, head turn,		group, $F(1,18) = 25.35$ , $p < .001$ , was	
		ball pass) X 2 (Leg:		significant."	
		left, right) mixed			
		design with			
		repeated measures			
		on the final two			
		factors			
Wulf & Toole	"If the beneficial effects of self-control	Two cell	Difference in	"The main effect of Group, $F(1,24) =$	F(1,24) =
(1999)	found in previous studies are more		means	4.54, p $< .05$ , was significant. Thus,	4.54
	general in nature (i.e., some general			allowing learners to select their own	
	mechanism responsible for these			schedule of physical assistance during	
	effects), learning advantage would			practice had a clearly beneficial effect on	
	also be expected for self-controlled			learning."	
	use of physical assistance."				

Wulf, Clauss,	"Importantly, however, if self-control	Two cell	Difference in	"Whereas the self-control group	F(1,24) =
Shea &	promotes the development of a more		means	demonstrated relative force onsets that,	4.43
Whitacre	efficient movement technique, one			on average, occurred about half the	
(2001)	should see greater movement			distance between the center of the	
	efficiency, as indicated by delayed			apparatus and the participant's	
	force onsets, in self-control as			$\   \text{maximum amplitude, the yoked group's}$	
	compared to yoked participants."			average force onset had already occurred	
				after they had travelled less than $20\%$ of	
				the distance to the maximum amplitude.	
				This group difference was significant,	
				F(1,24) = 4.43, p < .05."	
Wulf,	"Thus, if the learning advantages of	Two cell	Difference in	"Overall, the self-control group had	F(1,23) =
Raupach &	self-controlled practice generalize to		means	higher form scores than the yoked group	5.16
Pfeiffer	observational practice, allowing			throughout retention. The main effect of	
(2005)	learners to decide when they want to			group $F(1,23) = 5.16$ , $p < .05$ , was	
	view a model presentation should			significant."	
	result in enhanced retention				
	performance, with regard to				

movement form and, perhaps,

that of yoked learners."

movement accuracy, compared to

Wulf,	"The purpose of the present	Two cell	Difference in	"On the retention test one day later, the	F(1, 29)
Iwatsuki,	experiments was threefold. First, we		means	choice group demonstrated higher scores	= 5.72
Machin,	deemed it important to provide			than did the control group. The group	
Kellogg,	further evidence for the impact of			effect was significant, $F(1, 29) = 5.72$ , p	
Copeland, &	incidental choices on motor skill			< .05."	
Lewthwaite	learning. Given that self-controlled				
(2017) Exp 1.	practice benefits for learning have				
	frequently been interpreted from an				
	information-processing perspective				
	(e.g., Carter, Carlson, & Ste-Marie,				
	2014; Carter & Ste-Marie, 2016),				
	with limited regard for				
	rewarding-motivational explanations,				
	further experimental evidence for				
	learning enhancements through				
	choices not directly related to the				
	task seemed desirable (Experiments 1 $$				
	and 2)."				
Wulf,	"To summarize, we hypothesized that	2 (Autonomy	Difference in	"On the retention test, the main effect of	F(1,64) =
Chiviacowsky	an external focus and autonomy	support: self,	means	Autonomy Support was significant, F(1,	6.98
& Drews	support would have additive benefits	yoked) X 2 (Focus:		64) = 6.98, p < .01."	
(2015)	for motor learning (i.e., retention and	external, internal)			
	transfer performance), as evidenced				
	by main effects for each factor."				

Ikudome,	"Previous studies manipulating	2(Choice: self,	Difference in	"An ANCOVA indicated significant main	F(1,39) =
Kuo, Ogasa,	participants' choice of variables	yoked) X $2$	means	effects of choice, $F(1, 39) = 8.93$ , $p =$	8.93
Mori &	relevant to the experimental task	(Motivation: high,		.005."	
Nakamoto	have indicated that such choices have	low)			
(2019; Exp.	a positive effect on motor learning				
2)	due to deeper information processing				
	by the participants. Based on these				
	studies, it is possible that this				
	positive effect would be observed				
	regardless of participants' levels of				
	intrinsic motivation, because this				
	type of choice would not induce a				
	change in perceived locus of causality				
	from internal to external."				

Note. KR = Knowledge of results; PD = Parkinson's disease; SC = Self-controlled

# Appendix B

#### Missing data

- Of the 78 experiments that met the eligibility criteria of this meta-analysis, 25 were
- <sup>2</sup> excluded because of missing data. Those 25 experiments included 13 experiments that
- 3 reported a statistically significant result, along with 12 that failed to find a significant
- 4 self-controlled learning effect. Among the 13 experiments with missing data reporting a
- <sup>5</sup> significant self-control benefit, one reported an inappropriate analysis (Hemayattalab et
- 6 al.2013), one reported statistics that do not match the experimental design (Jalalvand et
- al., 2019),<sup>7</sup> one reported significant effects on a partial analysis of their data rather than
- 8 overall (Brydges et al., 2009), and one was previously identified by Lohse and colleagues
- 9 (2016) as an outlier study (Carter & Patterson, 2012). The meta-analysis may have been
- strengthened by the exclusion of these results (Stanley et al., 2010).

Among the remaining nine experiments reporting a significant effect with missing data, two reported effects collapsed across immediate and delayed retention only (Patterson et al., 2013; Wu & Magill, 2011), two reported null effects on a higher priority measure and did not include sufficient data to calculate the effect size, while reporting a significant effect on a lower priority measur((Wulf et al., 2001; Wulf et al., 2005, both studies were included in the primary *p*-curve analysis), and five compared three or more groups in an omnibus ANOVA and reported the group effect as significant but did not include sufficient data to calculate the effect size for the self-control versus yoked comparison (Chen et al., 2002;

Ghorbani, 2019; Huet et al., 2009; Janelle et al., 1997; Norouzi et al., 2016)

<sup>&</sup>lt;sup>6</sup> Although data were collected in one dimension using concentric circles, AE and a measure of dispersion were analyzed together in a MANOVA. This measure of dispersion is not an accurate reflection of variability on a two-dimensional task for reasons described by Hancock et al. (1995).

<sup>&</sup>lt;sup>7</sup> A subgroup analysis involving two groups n = 15 was reported with df = 56. The article reports  $r^2$  effect sizes associated with each test that cannot be reproduced with the reported statistics or best guesses.