Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Spontaneous Force Fluctuations as a window into the mind: methodological challenges and perspectives

Florentin Vandeville

florentin.vandeville@univ-catholille.fr

Université Catholique de Lille

Oliver Lindemann

Erasmus University Rotterdam

Olivier Capra

Université Catholique de Lille

Systematic Review

Keywords:

Posted Date: September 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10590267/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Spontaneous Force Fluctuations as a window into the mind: methodological challenges and perspectives

Florentin Vandeville[1], Oliver Lindemann[2], Olivier Capra[1]

[1*]Neurethic-Lab – ETHICS EA 7446, Université Catholique de Lille, Lille, F-59000, France.

[2*]Department of Psychology, Education and Child Studies, School of Social and Behavioural Sciences, Erasmus University Rotterdam, Rotterdam, Netherlands.

Contributing authors: florentin.vandeville@univ-catholille.fr; lindemann@essb.eur.nl; olivier.capra@univ-catholille.fr;

Abstract

Manual force measurement has been increasingly used in cognitive research, although it has been adopted with heterogeneous theoretical and methodological motivations. In particular, the analysis of spontaneous force fluctuations (SFFs) during cognitive task have been shown to reveal subtle involuntary motor signals that are sensitive to task demands and cognitive processes in different domains such as sensorimotor integration, emotion, language, action observation, and numerical cognition. The technical setup required to record manual force is relatively lightweight, but this apparent simplicity comes with methodological challenges regarding sensor selection, experimental constraints, data acquisition, preprocessing, and signal analysis. This review first classifies the main ways manual force has been used in cognitive studies, situating this emerging method within the existing literature. It then provides an extended methodological synthesis of SFF research, aiming to clarify current practices, identify sources of methodological variability, and argue for enhanced reporting standards and targeted methodological experiments as a necessary step toward the standardisation of SFF methodology.

Introduction

Psychologists have established a long tradition of measuring reaction times for the behavioural study of cognitive processes underlying fundamental skills such as attention, perception, memory, language, and number processing (Donders, 1969); see Lindemann and Fischer (2023) for a recent introduction to chronometric methods. Modern cognitive researchers have emphasised that not only the timing of responses, but also the strength or force with which responses are executed provides important insights into the underlying cognitive processes. For instance, Jaśkowski and colleagues reported that stimulus expectancy (Jaskowski & Verleger, 1993) as well as stimulus intensity (Jaśkowski, Rybarczyk, Jaroszyk, & Lemański, 1995) affect the force of button-press responses. In the same vein, Abrams and Balota (1991) observed that responses in a lexical decision task were not only faster for high-frequency words but also more forceful.

However, to get a deeper understanding of how cognition unfolds over time, the latencies or forces of ballistic responses might not be the most informative parameters, and continuous measures of behaviour such as eye or hand tracking have been proposed instead (see Laubrock et al. (2023), for a recent review of continuous methods). A rather novel approach to study such temporal dynamics of cognitive processes is the measurement of minor changes in the force with which participants hold an object (see e.g. Michirev, Lindemann, Kühne, Fischer, & Raab, 2024; Nazir et al., 2017)—a paradigm that we refer to here as "spontaneous force fluctuation" (SFF).

Over the past 15 years, the study of SFFs has emerged as an innovative approach to characterising cognitive processes, including their temporal unfolding, across domains such as spatial attention (e.g., Miklashevsky, 2022), action observation (e.g., Blampain, Ott, & Delevoye-Turrell, 2018), language processing (e.g., Nazir et al., 2017), and numerical cognition (e.g., Miklashevsky, Lindemann, & Fischer, 2021). The methodology is non-invasive and easily implementable: participants hold an object or sensor that measures for applied force while performing a cognitive task, without being explicitly instructed to modify their grip force. In every object holding action the applied motor force is not perfectly constant and slightly varies. These minor fluctuations, measured at the millinewton scale, can be correlated with the requirements or events in the cognitive task and provide this way a continuous indicator of the ongoing processing. The present article will provide a systematic review of studies that employed this SFF to study Human cognition.

We define SFF as systematic modulations of the force applied to an object that arise from processing demands in a concurrently performed cognitive task, without any explicit instruction to change force, that can be used to evaluate underlying cognitive processes. This type of measurement has been first applied in research on emotions to capture perceived stress or arousal (Coombes, Gamble, Cauraugh, & Janelle, 2008). More recent research reveals that the object holding force is not only affected by physiological stress responses, but also modulated during "cold" cognition. Frak, Nazir, Goyette, Cohen, and Jeannerod (2010) were among the first to apply SFF to study higher-level cognitive processes. The authors were interested to study motor activation while language processing and required their participants to hold a force sensor while listening to either motor-related words, such as *grasp*, or non-motor-related words,

such as *think*. Processing motor-related words produced an increase in grip force relative to non-motor-related words approximately 260 ms after word onset. This finding illustrated the potential of continuous force recording to reveal not only whether cognitive processing affects motor output, but also when this influence emerges. The study of (Frak et al., 2010) stimulated several studies in the field of cognitive psychology, which will be the focus of this review.

Despite the apparent simplicity of the setup, SFF measurement involves methodological choices concerning sensor characteristics, grip configuration, experimental procedure, signal preprocessing, artifact rejection, and statistical analysis. These choices have accumulated across a small and terminologically heterogeneous literature—no shared terminology currently exists to designate the paradigm—making relevant studies difficult to identify and methodological practices difficult to compare. Although Nazir et al. (2017) provided an early methodological discussion combined with some preliminary suggestions, the subsequent development of the field and the emerging diversity of study protocols, setups and statistical approaches to SFF calls for an updated synthesis of current practices and unresolved methodological issues.

To address these issues, the present review first classifies the main paradigms using force measurement to investigate cognition, thereby positioning this emerging method within the broader literature. It then provides an in-depth methodological synthesis of identified SFF studies, with the aim of identifying current practices and priorities for further standardisation.

Literature review

Method

The review procedure was inspired by the PRISMA guidelines (Page et al., 2021). A systematic literature search was conducted across four databases: PubMed, Scopus, APA PsycNet, and IEEE Xplore. The following search string was used:

> *("response force" OR "grip force" OR "response strength" OR "isometric force" OR "grasp force" OR "holding force" OR "continuous force" OR "isometric contraction") AND cognition*

The search was conducted on 10 February 2026 and returned 862 records: 519 from PubMed, 303 from Scopus, 30 from APA PsycNet, and 10 from IEEE Xplore. A custom Python script was used to identify 150 duplicate records based on their titles. After duplicates removal, 712 records remained for screening.

No standardised terminology currently exists for the SFF methodology, while force recording is used across a broad range of research fields and experimental paradigms. The search strategy was therefore designed to maximize the identification of potentially relevant studies without restricting the search to terminology specific to SFF. Thus, all studies combining force measurement with the investigation of cognitive processes were initially considered, and given the large and heterogeneous body of work this returned, the retrieved studies were organised according to the classification framework described below to identify those involving spontaneous force fluctuations (SFFs).

Inclusion and exclusion criteria

Studies were eligible for inclusion if they: (1) reported an experimental study; (2) included a measure of manual force analysed in relation to a cognitive process; (3) were published as peer-reviewed journal articles; and (4) were written in English.

Studies were excluded if they: (1) were conference papers, book chapters, books, reviews, or other non-experimental publications; (2) did not involve human participants; (3) included participants with a medical condition; or (4) could not be assessed because the full text was unavailable.

Classification of force-measurement paradigms

Studies combining force measurement with the investigation of cognitive processes constitute a substantial body of literature. To structure this literature and clarify the scope of the current review, we organised the studies into three classes based on the research question, and the manner in which force is used. Figure 1 shows the decision tree used to classify the studies.

Based on our eligibility criteria, we only considered studies in which force was used as a dependent variable. We first distinguished between studies that use force to look at the impact of a cognitive task on motor behaviour or to analyse an ongoing cognitive process. When the primary research question concerns the control of motor behaviour or performance in motor task, studies were assigned to **Class I**. In these studies, participants are for instance instructed to exert force as strongly or for as long as possible, or with temporal constraints, or to maintain a specific level of force. These paradigms examine how cognitive processes affect this motor behaviour (e.g., Cruz-Montecinos et al., 2018; Guillery, Mouraux, Thonnard, & Legrain, 2017).

The remaining studies, which did not focus on motor control, are characterized in our review by their aim to employ force measurements for the study of cognition. The paradigms of these studies have to be distinguished based on the key methodological difference in how the measured motor behaviour is connected to the cognitive task of interest. Some studies measure the force of active, instructed motor responses directly tied to the cognitive task. In contrast, others assess the force of a motor behaviour unrelated to the task, but performed simultaneously with it. That is, the further classification depends on whether the conclusions are based on instructed motor responses or spontaneous changes in behaviour. When participants were instructed to perform an active response to a stimulus, such as press of a force sensitive button, studies were assigned to **Class II**. Within this class, a small distinction can be made between paradigms requiring participants to modulate force according to an explicit instruction (e.g., Jaśkowski et al., 1995; Mattes, Leuthold, & Ulrich, 2002; Vierck & Kiesel, 2010) and paradigms in which participants simply press the sensor without any constraint on force magnitude (e.g., Mattes, Ulrich, & Miller, 1997). In both cases, response force was then analysed as a function of the experimental conditions to investigate cognitive processes.

When studies examined force fluctuations related to an ongoing cognitive process, studies were assigned to **Class III**. These studies included tasks such as the presentation of simple and salient auditory stimuli (e.g., Novembre et al., 2018) or emotional pictures (e.g., Blakemore, Rieger, & Vuilleumier, 2016) or higher cognitive processes

with language processing (e.g., Nazir et al., 2017) or numerical cognition (e.g., Miklashevsky et al., 2021). Importantly, this class corresponds to the SFF methodology and constitutes the primary focus of the present review.

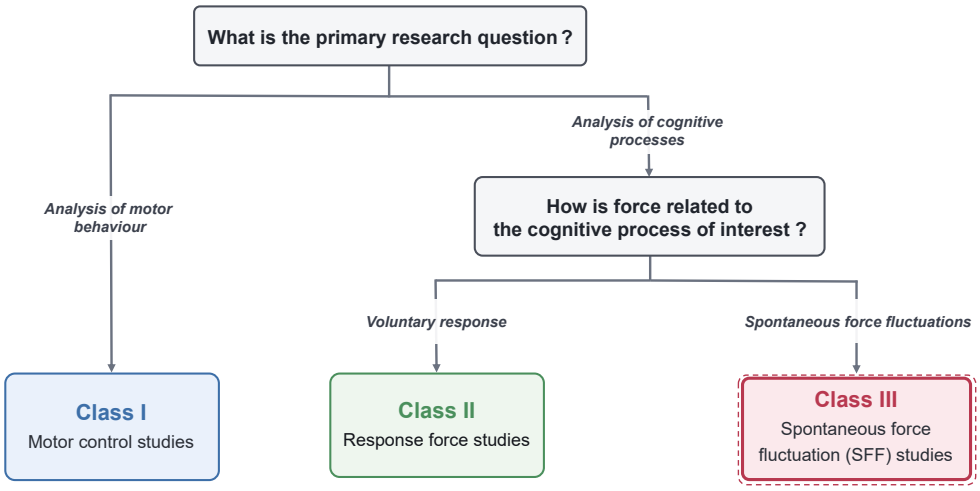


Fig. 1: Schematic representation of the classification of force studies. Decision tree based on research question and force usage for studies meeting the eligibility criteria. Among the 94 classified articles, Class I (44.68 %), Class II (30.85 %), and Class III (24.47 %), corresponding to the SFF paradigm examined in this review.

Screening

Titles and abstracts were screened against the eligibility criteria by one researcher and checked by a second researcher. This stage resulted in the exclusion of 612 records, including three additional duplicates. When sufficient information was available in the abstract, studies were also assigned provisionally to one of the force-measurement classes described above. Potentially relevant studies and studies for which classification remained uncertain were retained for full-text assessment.

Based on the abstracts and titles, we identified 46 articles that belonged to classes other than Class III. These were therefore excluded from the subsequent stage of screening. We selected 54 articles for full-text examination and classification. All potentially relevant manuscripts were independently reviewed and classified by the investigators. This process identified 13 articles corresponding to Class III, while 15 articles were excluded because they did not meet the eligibility criteria. The remaining articles were classified to determine the final distribution across classes.

In addition to the studies identified through the systematic screening process, 10 additional articles were identified through reference-list screening and included in the final Class III sample, resulting in a total of 23 articles (24.47 %) of the final classified

corpus of 94 articles. Within this corpus, 42 articles were assigned to Class I (44.68 %) and 29 articles to Class II (30.85 %).

Figure 2 presents the PRISMA flow diagram of the study selection process.

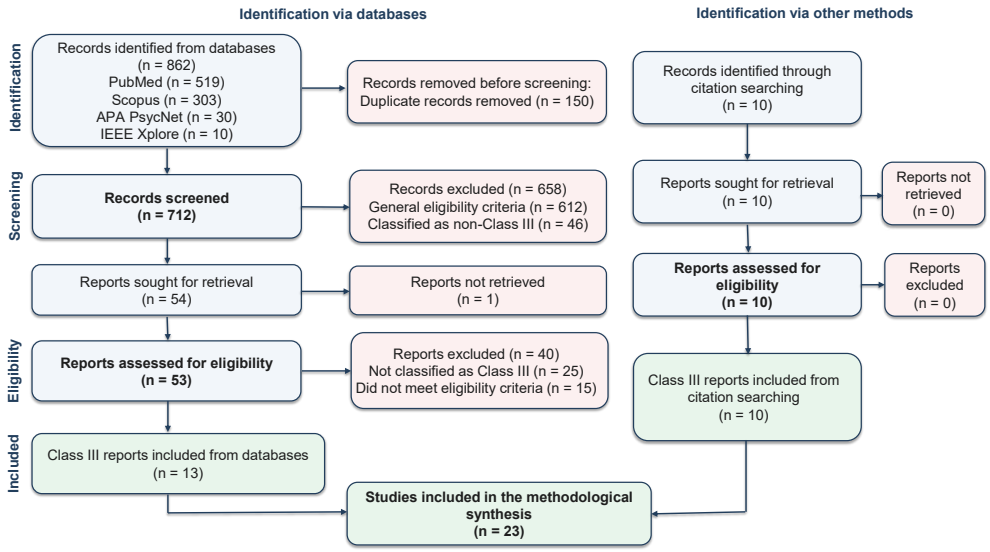


Fig. 2: PRISMA flow diagram of the study selection process, from the 862 records initially identified to the 23 SFF studies included in the methodological review.

Methodological synthesis of class III studies

The methodological synthesis focused on the identified 23 class III studies involving Spontaneous Force Fluctuation (Table 1). The full texts of all included studies were examined, and a predefined set of methodological elements was extracted. A detailed overview of the information reported by each study is provided in Appendix A. The complete report of the methodological elements for each study is available via the Open Science Framework (OSF): https://osf.io/x68yv/overview?view_only=bcb473e3f85b4ab983fef48713197d00

Sensor and apparatus specifications

We first extracted information on the sensor manufacturer and model, calibration[1], and resolution[2]. Sensors of the same model can be supplied with different calibrations and may therefore differ in measurement range and resolution. When resolution was not reported directly, we used the available information on the manufacturer,

[1] Sensor calibration refers to the mapping between applied force and signal output, thereby defining technical specifications such as resolution.

[2] Sensor resolution is the smallest change in the measured quantity that the sensor can reliably detect and distinguish.

Table 1: The 23 SFF studies included in the methodological review. Each article is given an identification number used to refer to it in the detailed report in Appendix A.

ID	Articles
1	Aravena, Courson, Frak, Cheylus, Paulignan, Deprez & Nazir, 2012
2	Aravena, Delevoye-Turrell, Deprez, Cheylus, Paulignan, Frak & Nazir, 2014
3	Blakemore, Rieger & Vuilleumier, 2016
4	Blampain, Ott & Delevoye-Turrell, 2018
5	Coombes, Gamble, Cauraugh & Janelle, 2008
6	Coombes, Naugle, Barnes, Cauraugh & Janelle, 2011
7	Da Silva, Labrecque, Caromano, Higgins & Frak, 2018
8	Da Silva, Santos, Mendes, Caromano, Higgins & Frak, 2019
9	Frak, Nazirn Goyette, Cohen & Jeannerod, 2010
10	Juárez, Labrecque & Frak, 2019
11	Labrecque, Descheneaux-Leroux, Castro & Frak, 2016
12	Michirev, Kühne, Lindemann, Fischer & Raab, 2023
13	Michirev, Lindemann, Kühne, Fischer & Raab, 2024
14	Miklashevsky, 2022
15	Miklashevsky, Lindemann & Fischer, 2021
16	Miklashevsky, Fischer & Lindemann, 2022
17	Naugle, Coombes, Cauraugh & Janelle, 2012
18	Nazir, Hrycyk, Moreau, Frak, Cheylus, Ott, Lindemann, Fischer, Paulignan & Delevoye-Turrell, 2017
19	Novembre, Pawar, Bufacchi, Kilintari, Srinivasan, Rothwell, Haggard & Iannetti, 2018
20	Novembre, Pawar, Kilintari, Bufacchi, Guo, Rothwell & Iannetti, 2019
21	Rangel, Novembre & Wessel, 2024
22	Reinecke, Nazir, Carvallo and Jayez, 2022
23	Tomassini, Maris, Hilt, Fadiga & D'Ausilio, 2020

model, and calibration to consult the corresponding technical documentation. We also examined the physical characteristics of the apparatus, including its thickness, total weight, and the material of the surface in contact with the fingers. Because the overall geometry of customised devices varied considerably between studies, thickness was retained as the most directly comparable dimension and as an approximate index of grip aperture.

65 % of the studies reported using sensors manufactured by ATI Industrial Automation, with the Mini40 (22 %) and Nano17 (13 %) being the most common models. Calibrations were reported in only three studies; two of them reported the corresponding force resolutions, and one could be inferred from the model and calibration with manufacturer's documentation, leading to different force resolutions of 3.125 mN, 10 mN and 20 mN. One study that did not use an ATI force sensor reported a resolution of 36 mN. Resolution could not be established for the remaining studies.

The physical characteristics of the apparatus were unevenly reported. The sensor thickness, which determines the crucial required grip aperture while holding, was reported in only 30 % of the articles (mean thickness of 1.83 cm, $SD = 0.21$). Total weight that participants were required to lift or hold was reported in 61 % of the studies ranging from 55 g to 267 g. The material of the finger-contact surface was specified in 39 % of the studies and included plastic, metal, and aluminium.

The size, weight and surface of force sensors are crucial object properties that strongly affect how the object is grasped and thus SFF measurements. However, our summary shows that these characteristics are often only partially reported. Because SFF captures fine-grained force dynamics in the millinewton range, particular attention should be paid to sensor resolution, calibration, and the properties of the contact surface. Technical documentation may supplement incomplete reporting by identifying factors that can affect signal quality, although it cannot substitute for a complete description of the recording setup. For example, some force sensor manufacturers recommend caution when mounting contact plates, as small particles or surface irregularities may introduce drift and hysteresis[3]. Moreover, room temperature may also affect measurement accuracy. Apparatus thickness, weight, and contact-surface material should also be documented, as these characteristics may influence grip aperture, the force required to hold the device, and the mechanical stability of the grip.

Future studies should provide sufficient technical and physical detail to allow the recording setup to be reproduced and its measurement properties to be assessed. More systematic reporting would facilitate comparisons across studies and help determine which sensor and apparatus characteristics are critical for reliable SFF measurement.

Grip configuration and participant posture

This section focuses on how the force sensor was handled and on participants' posture. The relevant information was derived from both textual descriptions and the photographs or schematic illustrations provided in the articles.

A representative example of the grip position used in most studies, together with its main variations, is illustrated in Figure 3.

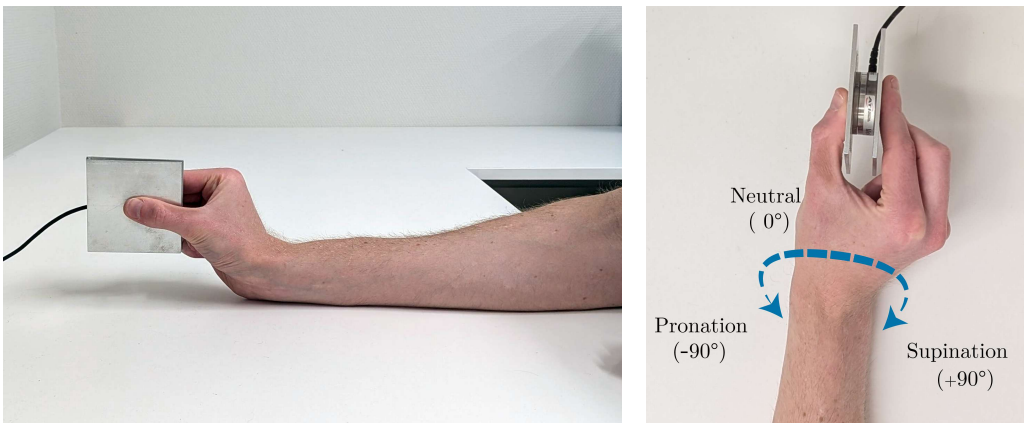
All reviewed studies except one required participants to hold the sensor in the hand; in the remaining study (Michirev, Kühne, Lindemann, Fischer, & Raab, 2023), participants placed their fingers on a fixed sensor. The sensor was held exclusively in the right hand in 65 % of the studies. A further 31 % investigated both hands, either through bimanual paradigms or by counterbalancing hand assignment. Da Silva et al. (2019) required participants to hold the sensor exclusively in the left hand.

Participants were reported to be seated in almost all studies except one, in which body position was not specified, and one, in which the participant was lying down (Blakemore et al., 2016).

83 % of the studies described forearm orientation, which was most commonly reported as neutral (52 %). In the remaining studies, the forearm was positioned with some degree of pronation or supination. Wrist position was reported in 91 % of the studies and was mainly described as neutral, with a slight inclination in two studies. Tomassini, Maris, Hilt, Fadiga, and D'Ausilio (2020) indicated that the wrist was abducted (deviated towards the thumb) during force production due to the use of a joystick to maintain the target force.

The wrist was supported on a surface in 61 % of the studies and unsupported in three studies. In almost all studies, the sensor itself was held above the table; the only exceptions involved a sensor mounted on a customised box fixed to the table (Michirev

[3]Hysteresis is a delay or inconsistency in the sensor's response when the applied force increases or decreases, causing the output to differ depending on whether the force is rising or falling.



(a) Side view (b) Top view

Fig. 3: Representative example of the grip configuration with side (a) and top view (b). This configuration represents the arm and the wrist in a neutral position. The wrist can be turned along the arm axis toward pronation or supination.

et al., 2023) and a custom-made isometric joystick equipped with load cells fixed on a support (Tomassini et al., 2020).

The fingers used to hold the sensor were specified in 91 % of the studies. A three-digit grip involving the thumb, index finger, and middle finger was used in 48 % of the studies. The remaining studies used a two-digit grip, most commonly involving the thumb and index finger, although one study used the index and middle finger.

Although no study has specifically assessed the effects of sensor handling or wrist and elbow support, the literature reviewed here suggests that SFF effects can be observed across a range of grip configurations. When the experimental design allows it, configurations that promote postural stability and limit fatigue should nevertheless be preferred in order to reduce motor variability unrelated to the cognitive process under investigation. Within these constraints, this apparent methodological flexibility may broaden the applicability of SFF to more ecologically valid settings, in which wrist position or the digits involved cannot be fully standardised. The current corpus remains relatively small, however, and dedicated studies will be needed to determine whether SFFs measures are genuinely robust to variations in sensor handling. To support such comparisons, future studies should systematically report participants' posture and provide both close-up and wider-view photographs of the experimental setup.

Individual factors

We extracted information on participants' age and handedness. We also examined whether participant exclusion criteria addressed motor impairments associated with medication or underlying medical conditions.

All studies reported participants' mean age, which ranged from 13 to 55 years ($M = 23.29, SD = 3.9$). Most studies included only right-handed participants (74 %). Four studies also included a small number of left-handed participants, mostly in bimanual configurations.

Participant exclusion criteria varied according to the objectives and requirements of each study. 39 % of the studies reported excluding participants with potential motor impairments related to medication or underlying medical conditions. However, the procedures used to assess these criteria, such as self-report, medical history, or formal motor assessment, were not always specified.

The reviewed studies included few older adults, although age may be relevant when the task involves a motor component. One SFF study found no significant relationship between age and the recorded force modulation (Da Silva et al., 2019). However, the narrow age ranges and the evidence from a single study do not allow firm conclusions. Dedicated studies are therefore needed to confirm whether age influences force modulation in SFF paradigms.

Motor conditions or treatments that may affect hand function could influence participants' ability to perform the grip task. Although their impact on SFF measures have not been specifically established, future studies should report whether such factors were considered in participant selection and how they were assessed.

Environmental and surface conditions

We examined whether the studies reported room temperature and humidity, as well as systematic cleaning of the sensor surface and participants' hands, because these factors may affect friction at the skin–sensor interface.

None of the reviewed articles reported room temperature or humidity or described systematic cleaning procedures for either the sensor surface or participants' hands. Novembre et al. (2019) indicated that the temperature of the experimental room was controlled but did not report any value. This absence of reporting does not establish that these factors were uncontrolled, but prevents assessment of their potential contribution to between-study variability.

Environmental and surface conditions may influence the mechanical coupling between the hand and the sensor. Although their effect on SFF measurements remains to be established, future studies should report relevant environmental conditions and describe any standardised procedures used to clean the sensor and participants' hands.

Experimental procedure

Holding the sensor continuously constitutes a low-force but sustained motor task and therefore requires consideration of several procedural factors. We reviewed the maximum continuous sensor-holding duration, the timing and duration of breaks, and the force targets that participants were required to reach and maintain before stimulus presentation. We also examined whether studies accounted for potential instrumental drift through systematic zero-offset correction procedure repeated during the experimental session. This procedure consists of periodically measuring the sensor output in the absence of applied force and realigning the signal so that this reference level corresponds to zero.

65 % of the studies reported the duration of continuous sensor holding. In these studies, the sensor was held continuously for periods ranging from 5.5 s to 4 min (M = 87.63 s, SD = 76.39 s).

Most studies reported providing participants with opportunities to rest by allowing them to release the force sensor between trials (87 %), although the timing and duration of these breaks varied. In seven studies, no fixed break duration was imposed, and participants determined when to resume the task. When a fixed duration was specified, it ranged from 5 s to 2 min. One study reported providing a break but did not specify its duration.

Most studies (87 %) required participants to reach a predefined force level before the start of a trial or block. This level could be fixed with arbitrary values (65 %) ; four of these studies used a fixed target of 1.5 N, whereas the others defined an acceptable force range, with reported values ranging from 1.5 N to 3 N. One study instead reported a target range of 0.08–0.13 V, which could not be converted into newtons because the force–voltage conversion parameters were not provided. Alternatively, the target level could be fixed as a percentage of the individual maximum voluntary contraction (MVC) previously established (22 %). The values ranged from 2 % to 35 % of participants' MVC. 44 % of the studies reported how long the target force had to be maintained, with durations ranging from 1.5 to 10 s.

Two of the reviewed articles explicitly reported performing a zero-offset correction at the beginning of each recording session (Novembre et al., 2018, 2019).

The procedural practices identified in the literature aim to optimise recording conditions by promoting stable sensor holding while limiting fatigue and potential instrumental biases, such as drift and hysteresis. Force decay over time has been reported in multiple studies (Blakemore et al., 2016; Coombes et al., 2008; Coombes, Naugle, Barnes, Cauraugh, & Janelle, 2011; Naugle, Coombes, Cauraugh, & Janelle, 2012; Nazir et al., 2017; Novembre et al., 2019) and should therefore be considered when designing the experimental setup. Tasks with moderate continuous holding durations may help limit fatigue and physiological force drift, while repeated zero-offset checks may reduce instrumental baseline drift between recording periods.

The use of a pretrial force target may further promote stable sensor holding by constraining the level of tonic motor engagement required to maintain a stable grip on the sensor. A sufficiently high target may help ensure stable mechanical contact and limit corrective adjustments, whereas an excessively high target may increase fatigue or background force variability.

Using a target range rather than a fixed value may preserve some interindividual flexibility while maintaining an acceptable level of sensor stability. However, dedicated studies are needed to determine whether the selected force level or range influences the amplitude, variability, or detectability of SFF effects.

Signal preprocessing

To characterise force-signal preprocessing in SFF studies, we reviewed the sampling rate, filtering procedures, and baseline correction. For filtering, we specifically examined the filter type and order, cut-off frequency, phase characteristics, and other reported parameters.

The sensor sampling rate was reported in 87 % of the studies. Reported sampling rates ranged from 100 Hz to 5000 Hz, with 1000 Hz being the most common (48 %). All studies applied some form of filtering or smoothing to the force signal. Most of the studies (74 %) applied a Butterworth low-pass filter, with the cut-off frequency set at 15 Hz in most cases and ranging from 10 Hz to 20 Hz in the remaining cases. All reported Butterworth low-pass filters were fourth-order filters, and all but four of the corresponding studies specified the use of zero-phase filtering. One study specified only the use of a low-pass filter with a cut-off frequency at 35 Hz. Three studies applied a band-pass filter with low cut-off frequencies between 0.1 Hz and 1 Hz and high cut-off frequencies between 30 Hz and 45 Hz; Novembre et al. (2019) specified the use of a third-order Butterworth filter. Two studies used alternative approaches: Reinecke, Nazir, Carvallo, and Jayez (2022) applied LOESS smoothing with a span of 0.15, and Blakemore et al. (2016) used a one-dimensional median filter with a window of 20 samples.

In all studies, force-signal analyses were stimulus-locked. That is, force-signal epochs were extracted around the onset of a stimulus of interest, with stimulus onset defined as time zero. Almost all studies (78 %) reported applying baseline correction, typically by subtracting the mean signal computed over a predefined time window preceding stimulus onset. The baseline window varied across studies, with its boundaries ranging from 400 to 5 ms before stimulus onset. In three studies, the baseline window was instead used as a reference for comparison with subsequent time windows (Blakemore et al., 2016; Coombes et al., 2008, 2011). Frak et al. (2010) did not report applying baseline correction and instead normalised the force signal using its minimum and maximum values for each participant.

The reported sampling rates were sufficiently high relative to the low-pass cut-off frequencies used in the reviewed studies. Even the lowest reported rate, 100 Hz, corresponds to a Nyquist frequency of 50 Hz, which exceeds the highest reported low-pass cut-off frequency of 35 Hz. The reviewed studies also showed substantial convergence in their use of low-pass filtering, particularly with respect to filter order and cut-off frequency. The widespread use of zero-phase filtering is particularly appropriate for SFF analyses because it avoids systematic temporal shifts in the filtered signal and thus preserves the timing of force modulations. Baseline correction was also widely used, consistent with the focus of SFF studies on relative force fluctuations rather than absolute force values. However, baseline duration varied across studies, and no specific justification for its selection was reported. Overall, the effects of these preprocessing choices on the amplitude and temporal profile of SFF modulations have not been systematically evaluated.

Data rejection

This section reports the criteria used to detect artifacts and reject trials, as well as the conditions under which a participant's data were excluded.

Although holding the sensor without voluntary movements or intentional changes in grip force is not particularly demanding, it may still require occasional corrective grip adjustments. The sensor may also capture unrelated mechanical disturbances, such as those caused by sneezing or external vibrations. Criteria are therefore needed

to detect these potential artifacts in the recordings and to reject affected epochs or trials from the statistical analysis.

78 % of the studies reported signal-based criteria for epoch or trial exclusion. Importantly, SFF analyses require the exclusion of epochs containing voluntary movements, because such movements produce large force changes that are unrelated to the process of interest and are therefore treated as noise. 43 % of the studies employed criteria taken from or derived from Nazir et al. (2017) to identify force changes likely to reflect voluntary movements. Nazir et al. (2017) proposed to exclude epochs if the minimum or maximum force deviated by more than 200 mN from baseline or if force changed by more than 100 mN within an interval of 100 ms.

Four studies modified the criteria and permitted a deviation from baseline up to 500 mN, notably to accommodate longer epochs in their experimental design. The criterion based on rapid force changes was omitted by some studies and increased slightly to 200 mN in one study. Labrecque, Descheneaux-Leroux, Castro, and Frak (2016) additionally identify outlying observations by applying the modified Thompson tau test (Thompson, 1935) in the rejection process.

Consistent with the criteria described above, Novembre and colleagues excluded trials in which force exceeded ±300 mN relative to baseline. Additionally, they applied a second criterion by excluding trials in which force fluctuations deviated by more than 3 (Novembre et al., 2018) or 4 (Novembre et al., 2019; Rangel, Novembre, & Wessel, 2024) standard deviations from the mean across trials.

The conditions under which an entire participant data set was excluded varied slightly across studies. In 35 % of the studies, a participant's data were excluded when the proportion of rejected trials exceeded a predefined threshold of either 20 % or 30 %.

Taken together, the criteria introduced by Nazir et al. (2017) were widely adopted and, in some studies, adjusted to trial duration or experimental design. These adaptations reflect the need to exclude voluntary or externally induced force changes without removing genuine SFF modulations. They also raise the question of whether fixed rejection thresholds should account for interindividual differences in force production and variability. As with pretrial force targets, for which some studies used ranges rather than fixed values (Section 2), rejection criteria might follow a similar rationale.

Statistical analysis of force data

We characterised data-analysis strategies according to the analysis domain and the method used to define temporal periods of interest. For each study, we identified whether force data were analysed in the temporal or spectral domain. Analytical approaches were further categorised as relying on theory-driven, data-driven, or a hybrid strategy combining both.

All studies except one analysed force profiles in the temporal domain. Among these, four studies additionally performed spectral analyses (Coombes et al., 2008; Nazir et al., 2017; Rangel et al., 2024; Tomassini et al., 2020). Only Novembre et al. (2019) performed a spectral analysis without any detailed temporal analysis of the force signal.

Two studies performed point-by-point t-tests across the analysed time course to detect SFF effects. However, as in many time-series analyses, adjacent samples in force

profiles are highly correlated. Consequently, statistical tests performed at different time points are not independent, resulting in a substantial inflation of the family-wise error rate. This issue can be addressed by defining time windows of interest (clusters) and performing a single statistical test on the data within each cluster.

Analyses employed in the present studies can be categorised along two dimensions: (a) the approach used to specify or define temporal regions. for testing differences in the profiles, and (b) the type of inferential statistics applied to test effects within the identified clusters. First, clusters of interest, in which force profiles are tested, can be predefined based on theoretical considerations or specific hypotheses. Such a theory-driven approach was used by 39 % of the studies. Alternatively, researchers may use a data-driven approach to identify time windows for subsequent testing. This approach was used by 52 % of the studies in our review. For example, Maris and Oostenveld (2007) proposed identifying clusters in time series data based on sample-wise statistics, defining a cluster as a sequence of consecutive samples whose sample-wise statistics exceeded a predefined threshold. Moreover, two studies adopted a hybrid strategy in which a broad predefined interval constrained a subsequent data-driven analysis (Juárez, Labrecque, & Frak, 2019; Labrecque et al., 2016).

After specifying the time windows of interest, the differences in the force profiles must be tested for significance. Some studies used frequentist statistics to test for systematic effects in the force profiles at the group level. To do this, studies in our review averaged the force data for each participant within each cluster and submitted them to parametric tests (12 studies), non-parametric tests (two studies) or linear mixed models (two studies, see Miklashevsky, 2022; Miklashevsky, Fischer, & Lindemann, 2022). Michirev et al. (2023) analysed cluster-averaged force data using Bayesian statistics.

A different approach, which does not rely on averaged data, involves permutation tests based on clusters (see Maris & Oostenveld, 2007, for details). These analyses perform sample-wise statistics (e.g., t-tests) and calculate the sum of statistics within the cluster. The null distribution of the maximum cluster-mass statistic is then approximated using repeated permutations and used to assess the significance of the observed clusters. Cluster-based permutation tests were used by five studies as a data-driven approach to analyse the signal as a whole and identify relevant temporal effects without specifying narrower windows a priori. This method was used by 58 % of the data-driven studies to identify temporally contiguous differences in the force signal.

These different strategies reflect the dual nature of SFF signals, in which an effect may be characterised by both its magnitude and its temporal profile. Predefined windows facilitate hypothesis-driven testing but depend on the relevance of their temporal boundaries to the paradigm under investigation. Whole-signal approaches impose fewer assumptions about effect timing, although the temporal extent of the resulting effects is determined by the statistical procedure itself. Hybrid approaches provide an intermediate strategy by constraining the analysis to a theoretically relevant period while retaining sensitivity to temporal variation within that interval. The predominance of temporal analyses is consistent with the high temporal resolution of force recording. A limited number of studies have investigated the frequency-domain and reported relevant frequency-domain effects (Novembre et al., 2019; Rangel et al.,

2024; Tomassini et al., 2020). However, these studies have exclusively focused on low-level cognitive processes. Notably, one of the few studies examining frequency-domain and higher-level cognitive processes did not report any effects (Nazir et al., 2017). These results do not allow us to determine whether spectral analysis is informative for SFF paradigms or whether its relevance is restricted to specific cognitive processes. Further research is needed to draw firm conclusions.

Theoretical rational of SFF studies

SFF has been applied across a wide range of research fields, including visual attention, emotion, action observation, psycholinguistics, and numerical cognition. For instance, the earliest SFF study identified in our review (Coombes et al., 2008) examined motor excitation elicited by emotional stimuli. The study showed an attenuated force decay when highly valenced emotional pictures (pleasant or unpleasant) were presented after participants reached a target force using visual feedback, and this effect was also observed at lower target force levels (Naugle et al., 2012). Subsequent work extended these findings by showing that the attenuated force decay was associated with individual differences in behavioural inhibition in response to unpleasant emotional pictures (Coombes et al., 2011). Blakemore et al. (2016) further investigated this effect using an fMRI-compatible force task and confirmed the effect only for unpleasant emotional stimuli.

Frak et al. (2010) investigated sensorimotor engagement during language processing. By showing that grip force varied more strongly when participants heard manual-action words than non-action words, they provided initial evidence that SFF could capture involuntary motor engagement associated with semantic processing. As these questions became more specific, later work increasingly incorporated the temporal dynamics of motor engagement. Subsequent language studies drew on Friederici's model of auditory sentence processing (Friederici, 2002) to analyse SFF data using time windows informed by EEG and fMRI research. This approach enabled a refinement of the underlying theoretical questions, showing, for instance, that the sensorimotor engagement associated with an action verb is modulated by whether the sentence in which it appears is affirmative or negative (Aravena et al., 2014, 2012). Consistent with these findings, Nazir et al. (2017) confirmed that the processing of action verbs, compared to non-action verbs, is differentially modulated within these theoretically grounded temporal windows.

By yielding interpretable effects within theoretically defined time windows, such analyses refined the investigation of language-related motor engagement while also illustrating the temporal sensitivity of the SFF paradigm. This temporal sensitivity subsequently motivated the combination of SFF with electrophysiological recordings. In an action-word paradigm, for example, Juárez et al. (2019) simultaneously recorded EEG and SFF and reported an association between the P200 ERP component and a concurrent increase in grip force.

The theoretical value of this temporal sensitivity extends beyond language. Miklashevsky et al. (2021) extended SFF research to numerical cognition, where force dynamics helped distinguish cognitive processes that could not be separated using reaction times alone. The temporal structure of the signal supported a two-step

account of number processing, characterised by distinct early and late components. Miklashevsky (2022) further showed that spatial information rapidly activates the manual motor system, eliciting an early grip-force response to both lateralised and centrally presented symbolic stimuli. In both studies, the temporal dynamics of the force signal were interpreted in relation to existing electrophysiological findings, illustrating the potential for cross-method interpretation.

SFF research in numerical cognition has also drawn on variations in signal amplitude. Several studies have reported larger grip-force variations for large than for small numbers, supporting an association between numerical and motor magnitude (Michirev et al., 2024; Miklashevsky et al., 2021). These findings illustrate how SFF can capture graded relationships between numerical magnitude and motor output, rather than merely indicating whether the motor system is engaged.

As in the language domain, theoretical questions have sharpened over time, moving towards the phenomenon of spatial–numerical associations, that is, observation in Western subjects that small numbers are associated with the left side of space and large numbers with the right. By relying on bimanual recording, SFF studies have been able to investigate these associations directly. The possibility of measuring the force of each hand independently and simultaneously confers a decisive advantage here: it reveals an inter-manual asymmetry that can be interpreted in terms of lateralisation, whereas reaction times provide access only to a single, global response. Miklashevsky et al. (2022) thus showed that these associations emerge in the absence of any lateralised motor response—an argument for their automaticity—while remaining modulated by the depth of numerical processing required by the task.

These domains illustrate how SFF can exploit the amplitude, the temporal structure, or the lateralisation of the force signal. Research on action observation shows that these properties can also be combined. Exploiting this combination, Blampain et al. (2018) found that the perceived intensity of an observed action is reflected in the amplitude of the grip-force response, while the timing of that response tracks the unfolding of the action scene.

By continuously capturing micro-fluctuations in motor engagement, the SFF paradigm provides a useful complement to established techniques in cognitive psychology and neuroscience. It combines sensitivity to variations in signal amplitude with fine-grained temporal information and can be implemented in unimanual or bimanual configurations, with the two hands recorded either simultaneously or in separate conditions.

SFF has also demonstrated its utility for characterising low-level cognitive processes. In particular, the presentation of salient stimuli elicits a consistent modulation of force, reflected in cortico-muscular coherence, as evidenced by force–EEG coupling (Novembre et al., 2018, 2019). Tomassini et al. (2020) indicated that visual detection is temporally coupled to cortico-motor dynamics, with EEG revealing alpha-band synchronization linking motor output and perceptual performance. SFF also provides a sensitive measure of non-selective motor inhibition, revealing its temporal dynamics and strong links to individual stopping performance (Rangel et al., 2024).

The interpretive value of this temporal information is further supported by evidence of convergence with electrophysiological measures: EEG (Juárez et al., 2019;

Novembre et al., 2018, 2019; Tomassini et al., 2020), EMG (Novembre et al., 2018; Rangel et al., 2024; Tomassini et al., 2020), and fMRI (Blakemore et al., 2016).

Beyond these signal characteristics, the equipment remains comparatively affordable—on the order of 15000 € for a sensor-and-acquisition setup—and offers valuable flexibility for moving research beyond the laboratory: into schools, hospitals, or even outdoor settings.

Table 2: Reporting frequency and typical value or range for the methodological items examined

Element	Reporting frequency (%)	Typical value / range
Sensor and apparatus specifications		
Sensor manufacturer	78	ATI
Sensor model	52	Mini40
Sensor calibration	13	SI-40-2
Sensor resolution	17	20 mN
Contact-surface material	39	plastic or metal
Sensor thickness	30	1.4–2 cm
Sensor weight	61	55–267 g
Grip configuration and participant posture		
Body position	96	seated
Hand used	100	right hand
Wrist angle	91	neutral
Forearm orientation	83	neutral
Wrist supported	74	yes
Fingers engaged	91	three digits
Sensor in contact with surface	83	no
Individual factors		
Age	100	13–55 years ($M = 23.29$, $SD = 3.9$)
Handedness	91	right-handed
Motor-related participant exclusion criteria	39	used for exclusion
Environmental and surface conditions		
Temperature	0	–
Humidity	0	–
Sensor cleaned	0	–
Hand-cleaning procedure	0	–
Experimental procedure		
Maximum continuous holding duration	65	5.5–240 s
Break information	87	5–120 s
Pretrial target force (value)	87	1.5–3 N
Pretrial target force (duration)	44	1.5–10 s
Zero-offset correction procedure	9	start of recording session
Data processing		
Sampling rate	87	1000 Hz
Filtering	100	low-pass: cut-off frequency 15 Hz
Baseline correction	78	from −400 ms to −5 ms relative to stimulus onset

Discussion

Among approaches examining force dynamics in relation to cognition, spontaneous force fluctuation (SFF) represent a rather novel and innovative methodology for research in cognitive psychology and neuroscience. A key advantage of this paradigm is its ease of implementation for experimenters, both in laboratory and field settings. Since merely holding an object is intuitive for participants and does not require additional cognitive resources, the method is well-suited to be used in conjunction with a cognitive tasks under investigation. However, the current review reveals the gradual accumulation of methodological practices, as well as differences in implementation, many of which lack direct empirical validation. In the following, we first consider how SFF research has provided valuable, time-resolved insights into cognitive processes and then highlight the methodological improvements needed in the short term and identify priorities for future research. These efforts are necessary to consolidate the paradigm and establish the methodological standards required for richer theoretical contributions.

The SFF paradigm complements established cognitive psychology and neuroscience methods by capturing micro-fluctuations in manual force. Although the method is relatively new and has so far been employed in only a limited number of studies, it has already been applied to a wide range of research questions in psychology. This method has demonstrated its ability to provide novel insights into cognitive processing across various domains of psychology. This diversity of theoretical questions to which SFF has been applied may also partially account for the variability in experimental protocols, recording procedures, and data analysis approaches that we have described and elaborated upon in this review.

However, it is important to notice that the explanations for changes in the force profile are highly diverse. Different researchers propose distinct underlying mechanisms responsible for SFF, suggesting a variety of cognitive processes at play. The proposed explanations include increased activation of motor processes (Aravena et al., 2012; Frak et al., 2010; Nazir et al., 2017), activation of size- and weight-related concepts (Michirev et al., 2024; Miklashevsky et al., 2021), task difficulty (Michirev et al., 2024), perceived stress and general physiological arousal (Naugle et al., 2012). We think that further research is required to achieve a more comprehensive understanding of the processes involved in spontaneous force fluctuations.

Towards methodological standardisation

In addition to the diverse theoretical motivations for using SFF, the research field is characterized by methodological heterogeneity across studies, which currently limits direct comparisons between findings. Terminology, acquisition parameters, preprocessing procedures, exclusion criteria, and statistical analyses are not always reported consistently and often differ substantially between studies. We therefore recommend two measures that can be implemented immediately, without requiring additional empirical data.

First, there is a need to establish a terminology. The term '*response force*' should be used deliberately and reserved for measurements of the force of voluntary response

in a given task. If force variations of a motor behaviour (such as the holding of an object) simultaneously performed and unrelated to the task of interest are recorded, we propose the term *spontaneous force fluctuation* (SFF; cf. Michirev et al., 2024). This term needs to be furthermore distinguished from research paradigms focussing on the examination of motor control processes and motor performances. Consistent use of this terminology would make the scope of the paradigm clearer and facilitate the identification and comparison of relevant studies.

Second, a core set of methodological information should be reported in force studies to ensure transparency, to enable replicability and to further analyse these methodological factors. At minimum, reports should specify the sensor and acquisition system, sampling rate, zero-offset correction, environmental conditions, target-force definition and instructions, feedback provided to participants, preprocessing steps, artefact-rejection and exclusion criteria, data-retention rates, and statistical analysis choices. Additionally, when relevant, hand dominance, grip configuration, participant posture, and timings of force maintenance and rest periods should also be documented. Establishing such reporting standards would immediately improve transparency, reproducibility, and cross-study comparability.

Methodological aspects of standardisation require dedicated empirical investigation. A particularly important issue concerns the criteria used to reject artefactual signal segments and to exclude trials or participants whose force deviates excessively from the target level (see Section 2). These criteria typically combine thresholds for abrupt force changes, such as variations exceeding 100 mN within 100 ms, with broader tolerances for force variability across trials. The latter vary substantially across studies, ranging from fixed margins of approximately ± 200 to ± 500 mN. Although these procedures are intended to ensure that the analysed signal reflects small spontaneous fluctuations around a sufficiently stable force level, their heterogeneity may produce markedly different rates of data and participant exclusion. Empirical work is therefore needed to determine which types and magnitudes of deviation materially compromise SFF measures, how rejection thresholds should account for individual target-force levels, and whether exclusion should operate at the level of signal segments, trials, or participants. Until such evidence is available, researchers should report the rationale for each threshold and its consequences for data retention and the final sample.

Similarly, the statistical approaches used to analyse SFF data vary considerably, both in how time windows of interest were defined and in the type of inferential test applied. Whether these methodological choices materially affect the sensitivity or reliability of the detected effects has not yet been investigated, and future validation work should give particular attention to statistical approaches capable of capturing the temporal dynamics of the signal rather than reducing it to single averaged values.

Beyond these priorities, validation studies should systematically assess how acquisition parameters, calibration procedures, target-force requirements, preprocessing choices, exclusion rules, and analytical strategies affect the amplitude and temporal characteristics of the SFF signal. Establishing this empirical basis is a necessary step towards more comparable, reproducible research and stronger theoretical inferences.

Scope and limitations

Given the extensive and diverse literature investigating the relationship between motor force and cognition and its widespread use in research, we adopted a pragmatic and structured approach for this review. To manage the breadth of the field, we focused our analysis on studies conducted with healthy adult participants, acknowledging that this selection was drawn from a subset of the broader literature.

The proposed categorisation of the force studies provides a first frameworks to organise and navigate this expansive body of research. The classifications does not claim to be exhaustive or definitive. Although the research question and the use of manual force provided a coherent basis for distinguishing between paradigms, this approach also encompassed heterogeneous studies within the same class. This was particularly the case for studies on sensorimotor integration (Novembre et al., 2018, 2019; Rangel et al., 2024; Tomassini et al., 2020) and emotion (Blakemore et al., 2016; Coombes et al., 2008, 2011; Naugle et al., 2012). In these studies, force primarily indexed a low-level cognitive mechanism rather than a modulation associated with the processing of specific cognitive or representational content. We decided not to further subdivide the studies in this classification in order to broaden the scope of application of this emerging and promising methodology.

Finally, we provide here a systematic literature review of studies examining Human cognition by measures of motor force and identified this way a rather complete pool of published studies using SFF. Although the method offers a rather novel and innovative approach that has not yet received significant attention in the research field, at least 23 studies have already been published. However, for the very reliable identification of methodological practices and standards, this number might still be considered small. It should also be critically noted that the homogeneity of certain methodological practices may reflect the contingency of shared research networks as much as genuine empirical validation. In this respect, the present work is intended as an invitation to further research, aimed at strengthening both the theoretical questions surrounding the nature of the recorded signal and the methodological consolidation of the paradigm.

Taken together, the current review highlights the theoretical contributions of the SFF paradigm across several cognitive domains, including emotion, motor inhibition, visual detection, language, action observation, and numerical cognition, and underscores the efficiency of its implementation. By directly capturing involuntary, millinewton-scale fluctuations in motor engagement during cognitive tasks, the approach enables a fine-grained characterisation of cognitive processes through a lightweight and affordable methodology.

Realising the full potential of this innovative approach will require greater methodological consolidation. The present synthesis provides an assessment of approximately fifteen years of research and identifies priorities for more systematic reporting and empirical validation and standardisation. This process needs to evolve alongside the ongoing utilisation of spontaneous force fluctuation, which serve as a new revealing window into cognitive processing.

Statements and Declarations

Public Significance Statement

The Spontaneous Force Fluctuation (SFF) paradigm offers a novel method to uncover the dynamics of cognitive processes—from emotion to numerical cognition—by capturing subtle, involuntary motor signals. While its lightweight implementation makes it accessible, realizing its full potential demands methodological standardization. This review summarizes the existing literature using this method and calls for more systematic reporting and empirical validation of methodological practices.

Funding

The authors would like to thank the Région Hauts-de-France for their financial support in the completion of this study.

Data availability

The data including the complete report of the methodological elements for each study can be found in OSF: https://osf.io/x68yv/overview?view_only=bcb473e3f85b4ab983fef48713197d00

Author contributions

Florentin Vandeville: Conceptualisation, Methodology, Formal analysis, Validation, Visualisation, Writing—original draft, Writing—review & editing. Oliver Lindemann: Conceptualisation, Methodology, Formal analysis, Validation, Writing—original draft, Writing—review & editing, Supervision. Olivier Capra: Conceptualisation, Methodology, Formal analysis, Validation, Visualisation, Writing—original draft, Writing—review & editing, Supervision.

ORCID IDs

Florentin Vandeville: https://orcid.org/0000-0002-1043-3067
Oliver Lindemann: https://orcid.org/0000-0003-3789-5373
Olivier Capra: https://orcid.org/0000-0002-1812-6061

References

Abrams, R.A., & Balota, D.A. (1991, May). Mental Chronometry: Beyond Reaction Time. *Psychological Science*, *2*(3), 153–157, https://doi.org/10.1111/j.1467-9280.1991.tb00123.x

Aravena, P., Courson, M., Frak, V., Cheylus, A., Paulignan, Y., Deprez, V., Nazir, T.A. (2014, April). Action relevance in linguistic context drives word-induced motor activity. *Frontiers in Human Neuroscience*, *8*, , https://doi.org/10.3389/fnhum.2014.00163

Aravena, P., Delevoye-Turrell, Y., Deprez, V., Cheylus, A., Paulignan, Y., Frak, V., Nazir, T. (2012, December). Grip Force Reveals the Context Sensitivity of Language-Induced Motor Activity during "Action Words" Processing: Evidence from Sentential Negation. *PLoS ONE*, *7*(12), e50287, https://doi.org/10.1371/journal.pone.0050287

Blakemore, R.L., Rieger, S.W., Vuilleumier, P. (2016, January). Negative emotions facilitate isometric force through activation of prefrontal cortex and periaqueductal gray. *NeuroImage*, *124*, 627–640, https://doi.org/10.1016/j.neuroimage.2015.09.029

Blampain, J., Ott, L., Delevoye-Turrell, Y. (2018, June). Seeing action simulation as it unfolds: The implicit effects of action scenes on muscle contraction evidenced through the use of a grip-force sensor. *Neuropsychologia*, *114*, 231–242, https://doi.org/10.1016/j.neuropsychologia.2018.04.026

Bray, S.R., Martin Ginis, K.A., Hicks, A.L., Woodgate, J. (2008, March). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology*, *45*(2), 337–343, https://doi.org/10.1111/j.1469-8986.2007.00625.x

Coombes, S.A., Gamble, K.M., Cauraugh, J.H., Janelle, C.M. (2008, February). Emotional states alter force control during a feedback occluded motor task. *Emotion*, *8*(1), 104–113, https://doi.org/10.1037/1528-3542.8.1.104

Coombes, S.A., Naugle, K.M., Barnes, R.T., Cauraugh, J.H., Janelle, C.M. (2011, December). Emotional reactivity and force control: The influence of behavioral inhibition. *Human Movement Science*, *30*(6), 1052–1061, https://doi.org/10.1016/j.humov.2010.10.009

Cruz-Montecinos, C., Calatayud, J., Iturriaga, C., Bustos, C., Mena, B., España-Romero, V., Carpes, F.P. (2018, September). Influence of a self-regulated cognitive dual task on time to failure and complexity of submaximal isometric force control. *European Journal of Applied Physiology*, *118*(9), 2021–2027, https://doi.org/10.1007/s00421-018-3936-6

Da Silva, R.L., Labrecque, D., Caromano, F.A., Higgins, J., Frak, V. (2018, February). Manual action verbs modulate the grip force of each hand in unimanual or symmetrical bimanual tasks. *PLOS ONE*, *13*(2), e0192320, https://doi.org/10.1371/journal.pone.0192320

Da Silva, R.L., Santos, F.F., Mendes, I.M.G., Caromano, F.A., Higgins, J., Frak, V. (2019, October). Contributions of the Left and the Right Hemispheres on Language-Induced Grip Force Modulation of the Left Hand in Unimanual Tasks. *Medicina*, *55*(10), 674, https://doi.org/10.3390/medicina55100674

Donders, F.C. (1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412–431, https://doi.org/10.1016/0001-6918(69)90065-1

Frak, V., Nazir, T., Goyette, M., Cohen, H., Jeannerod, M. (2010, March). Grip Force Is Part of the Semantic Representation of Manual Action Verbs. *PLoS ONE*, *5*(3), e9728, https://doi.org/10.1371/journal.pone.0009728

Friederici, A.D. (2002, February). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, *6*(2), 78–84, https://doi.org/10.1016/S1364-6613(00)01839-8

Guillery, E., Mouraux, A., Thonnard, J.-L., Legrain, V. (2017, November). Mind Your Grip: Even Usual Dexterous Manipulation Requires High Level Cognition. *Frontiers in Behavioral Neuroscience*, *11*, , https://doi.org/10.3389/fnbeh.2017.00220

Hiramatsu, Y., Kimura, D., Kadota, K., Ito, T., Kinoshita, H. (2015, September). Control of Precision Grip Force in Lifting and Holding of Low-Mass Objects. *PLOS ONE*, *10*(9), e0138506, https://doi.org/10.1371/journal.pone.0138506

Jaśkowski, P., Rybarczyk, K., Jaroszyk, F., Lemański, D. (1995, March). The effect of stimulus intensity on force output in simple reaction time task in humans. *Acta Neurobiologiae Experimentalis*, *55*(1), 57–64, https://doi.org/10.55782/ane-1995-1061

Jaskowski, P., & Verleger, R. (1993, August). A Clock Paradigm to Study the Relationship between Expectancy and Response Force. *Perceptual and Motor Skills*, *77*(1), 163–174, https://doi.org/10.2466/pms.1993.77.1.163

Johansson, R., & Westling, G. (1984, October). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*(3), , https://doi.org/10.1007/BF00237997

Johansson, R.S., & Westling, G. (1984). Influences of Cutaneous Sensory Input on the Motor Coordination During Precision Manipulation. C. von Euler, O. Franzén, U. Lindblom, & D. Ottoson (Eds.), *Somatosensory Mechanisms: Proceedings of an International Symposium held at The Wenner-Gren Center, Stockholm, June 8–10, 1983* (pp. 249–260). London: Palgrave Macmillan UK.

Juárez, F.P.-G., Labrecque, D., Frak, V. (2019, October). Assessing language-induced motor activity through Event Related Potentials and the Grip Force Sensor, an exploratory study. *Brain and Cognition*, *135*, 103572, https://doi.org/10.1016/j.bandc.2019.05.010

Keller-Ross, M.L., Pereira, H.M., Pruse, J., Yoon, T., Schlinder-Delap, B., Nielson, K.A., Hunter, S.K. (2014, April). Stressor-induced increase in muscle fatigability of young men and women is predicted by strength but not voluntary activation. *Journal of Applied Physiology*, *116*(7), 767–778, https://doi.org/10.1152/japplphysiol.01129.2013

Labrecque, D., Descheneaux-Leroux, R., Castro, A.A.G.D., Frak, V. (2016, November). Portable Device Validation to Study the Relation between Motor Activity and Language: Verify the Embodiment Theory through Grip Force Modulation. *International Journal of Engineering Research and*, *V5*(12), IJERTV5IS120003, https://doi.org/10.17577/IJERTV5IS120003

Laubrock, J., Miklashevsky, A., Kühne, K., Michirev, A., Jeglinski-Mende, M.A., Felisatti, A. (2023). Continuous methods: Eye tracking, hand tracking, and grip force recording. *Experimental Methods in Embodied Cognition.* Routledge.

Lindemann, O., & Fischer, M.H. (2023). Chronometric methods: Reaction times and movement times. *Experimental Methods in Embodied Cognition.* Routledge.

Maris, E., & Oostenveld, R. (2007, August). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190, https://doi.org/10.1016/j.jneumeth.2007.03.024

Mattes, S., Leuthold, H., Ulrich, R. (2002, October). Stimulus-response compatibility in intensity-force relations. *The Quarterly Journal of Experimental Psychology Section A*, *55*(4), 1175–1191, https://doi.org/10.1080/02724980244000152

Mattes, S., Ulrich, R., Miller, J. (1997). Effects of Response Probability on Response Force in Simple RT. *The Quarterly Journal of Experimental Psychology Section A*, *50*(2), 405–420, https://doi.org/10.1080/713755714

Michirev, A., Kühne, K., Lindemann, O., Fischer, M.H., Raab, M. (2023, June). How to not induce SNAs: The insufficiency of directional force. *PLOS ONE*, *18*(6), e0288038, https://doi.org/10.1371/journal.pone.0288038

Michirev, A., Lindemann, O., Kühne, K., Fischer, M.H., Raab, M. (2024, September). Spontaneous grip force fluctuations mirror semantic numerical magnitude processing: Larger numbers elicit larger forces. *Acta Psychologica*, *249*, 104468, https://doi.org/10.1016/j.actpsy.2024.104468

Miklashevsky, A. (2022, July). Catch the star! Spatial information activates the manual motor system. *PLOS ONE*, *17*(7), e0262510, https://doi.org/10.1371/journal.pone.0262510

Miklashevsky, A., Fischer, M., Lindemann, O. (2022, November). Spatial-numerical associations without a motor response? Grip force says 'Yes'. *Acta Psychologica*, *231*, 103791, https://doi.org/10.1016/j.actpsy.2022.103791

Miklashevsky, A., Lindemann, O., Fischer, M.H. (2021, January). The Force of Numbers: Investigating Manual Signatures of Embodied Number Processing. *Frontiers in Human Neuroscience*, *14*, 590508, https://doi.org/10.3389/fnhum.2020.590508

Naugle, K.M., Coombes, S.A., Cauraugh, J.H., Janelle, C.M. (2012, June). Influence of emotion on the control of low-level force production. *Research Quarterly for*

Exercise and Sport, *83*(2), 353–358, https://doi.org/10.1080/02701367.2012.10599867

Nazir, T.A., Hrycyk, L., Moreau, Q., Frak, V., Cheylus, A., Ott, L., ... Delevoye-Turrell, Y. (2017, February). A simple technique to study embodied language processes: The grip force sensor. *Behavior Research Methods*, *49*(1), 61–73, https://doi.org/10.3758/s13428-015-0696-7

Novembre, G., Pawar, V.M., Bufacchi, R.J., Kilintari, M., Srinivasan, M., Rothwell, J.C., ... Iannetti, G.D. (2018, February). Saliency Detection as a Reactive Process: Unexpected Sensory Events Evoke Corticomuscular Coupling. *The Journal of Neuroscience*, *38*(9), 2385–2397, https://doi.org/10.1523/JNEUROSCI.2474-17.2017

Novembre, G., Pawar, V.M., Kilintari, M., Bufacchi, R.J., Guo, Y., Rothwell, J.C., Iannetti, G.D. (2019, September). The effect of salient stimuli on neural oscillations, isometric force, and their coupling. *NeuroImage*, *198*, 221–230, https://doi.org/10.1016/j.neuroimage.2019.05.032

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., ... Moher, D. (2021, March). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71, https://doi.org/10.1136/bmj.n71

Rangel, B.O., Novembre, G., Wessel, J.R. (2024, August). Measuring the nonselective effects of motor inhibition using isometric force recordings. *Behavior Research Methods*, *56*(5), 4486–4503, https://doi.org/10.3758/s13428-023-02197-z

Reinecke, R., Nazir, T.A., Carvallo, S., Jayez, J. (2022, September). Factives at hand: When presupposition mode affects motor response. *Journal of Experimental Psychology: General*, *151*(9), 2173–2194, https://doi.org/10.1037/xge0001167

Slifkin, A.B., & Newell, K.M. (1999, June). Noise, information transmission, and force variability. *Journal of Experimental Psychology. Human Perception and Performance*, *25*(3), 837–851, https://doi.org/10.1037//0096-1523.25.3.837

Slifkin, A.B., Vaillancourt, D.E., Newell, K.M. (2000, October). Intermittency in the control of continuous force production. *Journal of Neurophysiology*, *84*(4), 1708–1718, https://doi.org/10.1152/jn.2000.84.4.1708

Thompson, W.R. (1935, December). On a Criterion for the Rejection of Observations and the Distribution of the Ratio of Deviation to Sample Standard Deviation. *The Annals of Mathematical Statistics*, *6*(4), 214–219, https://doi.org/10.1214/aoms/1177732567

Tomassini, A., Maris, E., Hilt, P., Fadiga, L., D'Ausilio, A. (2020, October). Visual detection is locked to the internal dynamics of cortico-motor control. *PLOS Biology*, *18*(10), e3000898, https://doi.org/10.1371/journal.pbio.3000898

Vierck, E., & Kiesel, A. (2010). Congruency effects between number magnitude and response force. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(1), 204–209, https://doi.org/10.1037/a0018105

Appendix A Detailed table for methodological aspects

Table A1: Articles identified by their ID (defined in Table 1) reporting each methodological element.

Element	Articles ID
Sensor and apparatus specifications	
Sensor manufacturer	1–7, 9, 12–16, 18–22
Sensor model	1, 3–7, 12, 13, 19–21, 23
Sensor calibration	4, 7, 20
Sensor resolution	3, 4, 7, 20
Contact-surface material	3, 10, 11, 13–16, 19, 20
Sensor thickness	10–16
Sensor weight	1, 2, 4, 7, 9–16, 18, 22
Grip configuration and participant posture	
Body position	1–12, 14–23
Hand used	1–23
Wrist angle	1, 2, 4–10, 12–23
Forearm orientation	1–4, 7–16, 18–21, 23
Wrist supported	1, 2, 4, 7–11, 14–16, 18–23
Fingers engaged	1–12, 14–22
Sensor in contact with surface	1, 2, 4, 7–16, 18–23
Individual factors	
Age	1–23
Handedness	1–5, 7–18, 20–23
Motor-related participant exclusion criteria	3–5, 7, 8, 13–16
Environmental and surface conditions	
Temperature	–
Humidity	–
Sensor cleaned	–
Hand-cleaning procedure	–
Experimental procedure	
Maximum continuous holding duration	1–9, 11, 13, 17, 18, 20, 23
Break information	1–4, 7–20, 22, 23
Pretrial target force (value)	2–8, 11–23
Pretrial target force (duration)	3, 5, 6, 12–17, 23
Zero-offset correction procedure	19, 20
Data processing	
Sampling rate	1–3, 5–14, 17–23
Filtering	1–23
Baseline correction	1, 2, 4, 7, 8, 10–16, 18–23