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# Nanotechnology and Ethics: The Role of Regulation Versus Self-Commitment in Shaping Researchers' Behavior

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**Abstract** The governance of nanotechnology seeks to limit its risks, without constraining opportunities. The literature on the effectiveness of approaches to governance has neglected approaches that impact directly on the behavior of a researcher. We analyze the effectiveness of legal regulations versus regulation via self-commitment. Then, we refine this model by analyzing competition and autonomy as key contingency factors. In the first step, qualitative interviews with nanotechnology researchers are conducted to reflect this model. In the second step, its empirical relevance is tested using a survey of 90 nanotech researchers. The results indicate that legal regulations, as well as self-commitment to an informal CoC reduce the scope of behavior. Finally, that competition and autonomy affect the relative strength of these governance factors.

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## Introduction

Nanotechnology research is the science and technology of controlling matter at the nanoscale (which ranges from approximately 1 to 100 nm). It has tremendous potential for solving core issues in society, in areas such as medicine, agriculture, environmental science, and engineering (Berger et al. 2008; Haas 2009; Kuzma and Besley 2008; Linton and Walsh 2008b). Despite these benefits, researchers and policy-makers alike have demonstrated that there are risks and uncertainties in nanotechnology (Bailey and Lattimore 2004; Clarke 2005; Davies 2007). These benefits and risks become more strongly and widely felt with each step toward large-scale use of nanotechnology.

Consequently, a research stream on nanotechnology governance has evolved, which focuses on the potential societal and ethical implications of nanoscale science and technology (Linstone 2011). Whereas some research is concerned with the liability of products containing nanoparticles, that is the dangers of nanotechnology to human health or the natural environment (Bailey and Lattimore 2004; Berger et al. 2008), other research activities deal with the production safety of nanotechnology (Haas 2009; Roco and Bainbridge 2001). The relevance of this research stream is underpinned by the emergence of institutions whose efforts are aimed at regulating production processes involving nanoparticles, and the introduction of "safe" nanoproducts to the market (e.g., the Environmental Protection Agency, the American Food and Drug Administration, Occupational Safety and Health Administration, etc.).

While the previous literature on nanotechnology regulation has tended to focus on new product introduction and production safety, the regulatory impact on the researchers themselves has received little attention. Exceptions include the papers by Fisher (2007), who shows that a self-critical environment fosters the capacity to make ethical research decisions, and by Petersen and Anderson (2007), who find that nanotechnology researchers tend to have a positive perception of the risk–reward balance of nanotechnology. This dearth of publications on the subject is deplorable, as it is the researchers who play a key role in shaping the direction of a research field (Knorr 1977).

A variety of approaches to nanotechnology regulation have been discussed (Bowman and Hodge 2008). The literature argues that legal regulations are difficult to design and implement for new technologies such as nanotechnology. First, new technologies are characterized by dynamism and contingent developments. Second, policy-makers cannot define what should be done and the legislators cannot define what is forbidden, as future developments are unknowable (van Calster 2008). In view of these shortcomings of legal regulation for new technologies, self-regulation via self-commitment has been discussed as an attractive alternative for regulating nanotechnology (Lee and Jose 2008; Siegrist et al. 2007). Self-commitment is understood here as the individual researcher's commitment to ethical research behavior. Self-committed researchers are accountable to themselves for their behavior.

We investigate the relative effectiveness of legal regulations and that of self-regulation via self-commitment in shaping the scope of research behavior at the level of the individual researcher. In addition, we analyze the influence of institutional contingencies (autonomy and competition) on the restraining effects of these two methods. Thereby, we contribute to the literature on nanotechnology regulation by focussing on the researchers as key agents. Based on the current literature, we propose a model and refine the concepts through a qualitative study. In a second, quantitative study, we test the model using a survey of 90 nanotechnology researchers. In this way, our results give theoretically and empirically rooted and practically relevant insights for nanotechnology researchers and for the policy-makers who design governance mechanisms for nanotechnology.

## Potential Benefits of Nanotechnology

From an economic perspective, nanotechnology has huge benefits (Thukral et al. 2008; Wonglimpiyarat 2005). Products that use nanomaterials include cosmetics, paints, the glare-reducing coating for eyeglasses and cars, sporting goods, sunscreens, stain-resistant clothing, and organic light emitting diodes used in laptop computers, cell phones, and digital cameras (Luther 2004). The economic scale of nanotechnology is manifested in a global market with an estimated value of $US 45.5 billion and a potential global workforce of between 0.8 and 2.0 million people. More than 30 governments have already implemented national nanotechnology initiatives, with a global R&D investment of $US 4.6 billion in 2004 alone. The commitment made by governments has been matched by private sector investment from companies such as IBM, NEC, Monsanto, and Du Pont (Bowman and Hodge 2008).

From a technology management perspective, breakthroughs in nanotechnology research can promote systemic economic progress: Nanotechnology holds great promise in terms of reducing life-cycle costs through lower failure rates, developing innovative devices based on new principles and architectures, improving productivity through the use of molecular/cluster manufacturing and creating entirely new industries (Linton and Walsh 2004; Roco and Bainbridge 2005). In contrast to the common paradigm of new technologies being initially more costly and only achieving better performance than existing applications in the long run, nanotechnology offers completely new applications that are cheaper from the outset, such as chemical manufacturing within the mass production of nanoelectronic circuits, for example, as opposed to current methods which use lithography in microelectronics (Roco and Bainbridge 2001).

From an environmental perspective, nanotechnology has great potential to provide new techniques for environmental remediation, monitoring and green production (Haas 2009) and to reduce emissions. As nanomaterials are lighter and stronger, they can be used to develop more fuel-efficient airplanes and hybrid cars to reduce energy consumption. Field tests, for example, indicate that iron nanoparticles can be used to clean up soil, by neutralizing contaminants such as polychlorinated biphenyls, DDT, and dioxins (Hood 2004). However, the greatest promise that nanotechnology holds for the environment may be the manner in which they could fundamentally change the way goods are manufactured (Bergeson and Auerbach 2004). Requiring fewer amounts of raw materials and generating less waste and hazardous byproducts, nanotechnology allows for building from the bottom-up, using only those molecules that are needed for the product (Luther 2004).

From a societal perspective, nanotechnology promises major advantages for humanity through health and medical advances (Bowman and Hodge 2007; Brownsword 2008; Romig Jr. et al. 2007). Living systems are governed by molecular behavior at the nanometer scale, where biology, chemistry, physics, and computer simulation all converge. The use of nanofabricated surfaces and devices will lead to better diagnostics and therapeutics, through more efficient genome sequencing and detecting the genes' expression, which facilitates optimal drug usage (Roco and Bainbridge 2001). Societal benefits induced by nanotechnology may also emerge on the labor market, by leading to significantly increased real wages and an improved standard of living, with only a transitional increase in unemployment as labor and capital are shifted to new, more valuable uses, from those that have been superseded or made less valuable (Bowman and Hodge 2006; Roco and Bainbridge 2005). Nanotechnology will not only displace older methods but is also likely to stimulate innovation in older technologies, which will make them more competitive (Roco and Bainbridge 2001).

## Potential Risks of Nanotechnology

Despite this great promise, nanomaterials also carry substantial risks that are difficult to predict. The sheer variety of applications, properties, routes of exposure, and means of disposal make it extremely challenging to identify, estimate, and manage the risks posed (Breggin and Carothers 2006). There is virtually no information available on how nanoparticles behave in the air, water or soil, or their potential to accumulate in food chains (Davies 2007). Knowledge of the chemical properties of a substance when in bulk may not help to predict how that substance will behave at the nanoscale (Goldberg 2009). For example, aluminum is inert when it takes the form of a soda can, but is highly explosive in nanoform.

Research that addresses the health risks of exposure to nanomaterials is only just beginning (Luther 2004). Hence, there is only limited data available on its effect on human health and the environment (Bergeson and Auerbach 2004; Dorbeck-Jung 2007). Moreover, the methods and protocols needed to detect, measure, and characterize nanomaterials are, in many cases, still under development (Lee and Jose 2008). Even at this early stage, health concerns are being voiced. For example, pulmonary exposure to nanomaterials is being discussed as they can, in comparison to larger, solid materials, more easily enter into the lung tissue. Particles deposited in the lungs can lead to chronic lung disease, which makes the epidemiologically surveyed association between inhaled nanoparticles and adverse health effects biologically plausible (Haas 2009).

## Research on Nanotechnology: The Research Process, Decisions, and Regulations

Given the potential benefits and risks of nanotechnology, the question of who should make decisions about the pursuit of particular nanotechnology research programs, and how they should do so, becomes important (Linton and Walsh 2008b; Romig Jr. et al. 2007). In scientific processes, there are many decisions that are taken by the individual researcher and that are not a direct consequence of the research program. Each decision taken by a researcher has a tremendous impact on the outcome and effects of the research and thus on the resulting body knowledge in that field (Knorr 1977).

Thus, the outcomes of nanotechnology research and its impact on society depend on the behavior of the researchers. As the future behavior of a researcher is contingent, and the benefits and risks of research activities do not become visible at the same time, researchers have some leeway to engage in opportunistic research behavior, i.e., research behavior that taps the potential of nanotechnology without taking into account the risks involved. Two factors influence this leeway:

First, it is proportional to the opportunities (control loopholes) for unethical conduct (leeway for opportunism). Second, it depends on the likelihood that the researchers will take advantage of the control loopholes. Thus, a key variable for the reduction of behavioral uncertainty is the limitation of the scope of research behavior within which an individual researcher operates: Not everything that is technically feasible and promising from a research perspective may in practice be researched. The scope of research behavior is represented by the activities that are carried out by the researcher. This scope may be restricted by (1) reducing the room for opportunistic behavior by imposing legal regulations or (2) reducing the researcher's inclination to engage in opportunistic behavior by encouraging self-commitment to a code of conduct (CoC).

### Governance Through Legal Regulation

Leeway to engage in opportunism results from incompletely specified property rights (O'Driscoll and Hoskins 2006). Opportunistic research behavior is that which taps into the potential of nanotechnology without taking into account the risks associated with it. One way to reduce this leeway is to specify property rights further by developing legal regulations. Such hierarchical regulatory structures (1) define what is forbidden by law, (2) attach an explicit sanction to misconduct and (3) impose a control regime for detecting misconduct. Here, legal regulation can be defined as the set of legal requirements applicable to nanotechnology research and commercial applications, including rules generated and enforced by government regulatory agencies (e.g., the FDA) and statutes enacted by legislature (Bowman and Hodge 2006).

If researchers are interpreted as rational actors that conduct research to maximize their research-related utility (Kyobe 2009), the researcher's bottom line of benefits and costs can be influenced by making certain behavioral options more, or, respectively, less, attractive. Socially unfavorable research behavior can be made less attractive for the researchers by labeling it as illegal and attaching additional costs (sanctions) to it. To prevent such behavior, there must be (1) a credible likelihood of detecting violations, (2) fast, certain, and appropriate sanctions imposed upon detection, and (3) an intense perception among researchers of these detection regimes and sanctions (Friedman 1975; Posner 1997). The additional costs imposed on a researcher who has engaged in misconduct not only comprise monetary costs but also restricted access to resources. In this way, legal regulations restrict the individual scope of the researcher's research behavior.

**H1** The more intensely the researchers perceive legal regulations on nanotechnology, the more they restrict the scope of their individual research behavior.

## Governance by Self-commitment to a CoC

Legal regulations in the field of nanotechnology are difficult to design and enforce (Guerra 2008; Muris 1981). First, to establish effective legal norms, law makers need to know beforehand what type of behavior is actually socially desirable. However, this requires researchers to share valuable knowledge with the public (Park and Ungson 2001) without having the ability to protect this knowledge from competitors (Davies 2007). Second, to effectively enforce the legal regulations, authorities need to monitor the behavior of the individual researchers and identify unlawful behavior ex post (Dwyer et al. 1987). Due to the dynamic development of nanotechnology and the lack of knowledge as to its effects, these requirements cannot be met sufficiently in this field (Davies 2007). For Lee and Jose (2008, p. 116), legal regulations will thus "be a matter of difficulty because of the time taken both to learn of the social consequences of the technology and to adapt regulatory structures as instruments of control." Third, credible threats require sufficient sanctioning power over the nanotechnology researchers. However, a lack of in-depth knowledge of nanotechnology among the judicative makes this difficult. In addition, executing sanctions in research networks that span national borders is difficult. As a result, it would be impossible to set up effective legal regulations for large areas of nanotechnology research (Lee and Jose 2008; van Calster 2008) and the public is thus confronted with weakly specified legal regulations and inadequate law enforcement (van Calster 2008).

In situations where regulations are similarly toothless in terms of ensuring socially favorable conduct, such as in cooperative internationalization (Fink et al. 2008; Fink and Kessler 2009) or in R&D alliances (Adler 2001; Ring and van den Ven 1992), the extant research discusses the coordination of individual behavior through self-commitment to a set of maxims. These maxims are either *formally* represented as CoCs or *informally* existent as internalized behavioral boundaries. As adherence to formal or informal CoC is based on self-commitment (see the ensuing argument), they are treated in this theory section together.

Here, we understand formal and informal CoCs to mean ethical codes that comprise (formal) "statements of what [a community] expects in the way of ethical behavior" (Ferrell and Fraedrich 1994, p. 170) and that contain values (e.g., honesty and integrity) and obligations related to these social values (Gaumnitz and Lere 2002; Knouse et al. 2007). Such codes are often embedded in ethics programs, which are "a coherent set of actions directed primarily at the operational level to stimulate morally responsible behavior of persons" (McDonald and Nijhof 1999, p. 133) in a specific community. These CoCs are predominately internally motivated rather than introduced in response to external pressure (Boyd 1996).

Adherence to a COC aligns the behavior of the community's members with its values (Ferrell et al. 1998; McDonald and Nijhof 1999). Maitland (1985, p. 138) states the following: "A code of conduct—even if only morally binding—can be expected to exert a powerful constraining influence on the behavior of would-be defectors." In the case of misconduct, researchers who evaluate their own behavior against the backdrop of a (informal) CoC feel uncomfortable with themselves, even if they are accountable only to themselves.

The maxims communicated in these codes evolve from discourse within the research community, and are shaped at the forefront of the field. However, the development of these maxims does not take place in isolation. As members of society, researchers have to justify their maxims through public discourse, which ensures that the values and norms of the society, as well as general and group-specific risks, are considered. Within the public discourse, a tacit CoC evolves through the framing of the evaluation of future behavior through the evaluation of past behavior (Schuetz 1972). The evolution of an informal CoC from within the research community ensures that the potential of nanotechnology is tapped (Berger et al. 2008).

In terms of the behavioral coordinative power of the CoC, the unfolding of maxims is not in itself enough. The researchers need to adhere to these maxims, based on self-commitment, and to evaluate their own behavior against the backdrop formed by them. In this way, they are accountable to themselves for complying with their maxims (Haase 2008). The Austrian writer Friedell (1983) described this social mechanism as follows: "The most reliable way to make people decent is to take them for decent." While self-commitment reduces the researchers' inclination to engage in opportunistic behavior, the latitude for such behavior is still maintained. Thus, it is the researchers' intrinsically motivated commitment to ethical conduct that impedes socially unfavorable behavior, and the researchers are accountable to themselves (Nooteboom 1996). In this respect, mutual uncertainty may be overcome if the researchers expect ethical behavior from each other and thus behave ethically themselves (Luhmann 1988; Williamson and Craswell 1993). For such mutual expectation to evolve, the researchers must plausibly communicate their self-commitment to each other and the public. They can achieve this effectively by committing themselves to a CoC.

Individual behavior is based on personal intentions that can change over time (Trevino 1986). The communication of organizational norms through a CoC can influence the personal intentions of nanotechnology researchers and may motivate them to commit themselves to these norms. As the code embodies good practice and so serves as a standard against which the individual behavior of researchers can be judged, it has the potential to reduce behavioral uncertainty (Maitland 1985). If the CoC has been embedded in organizational processes and routines, it can lead to the emergence of responsible individual behavior (Nijhof et al. 2003).

**H2** The more the researchers are self-committed to a code of conduct, the more they restrict the scope of their individual research behavior.

## Autonomy and Competition as Moderators

Nanotechnology researchers do not work in isolation, but are members of research groups, research institutes or companies, and a professional community. Thus, they are embedded in a close-knit fabric of norms, and corresponding expectations. Thus, the individual researcher's behavior takes place in a well-observed and highly structured arena. Here, legal regulations and restrictions based on self-commitment to a formal or informal CoC constitute behavioral corridors, which define the expected behavior (Schuetz 1972). In the case of corridors defined by legal regulations, the researchers are mainly answerable to an external authority. In the case of those defined by self-commitment to a formal or informal CoC, they are answerable to their peers and, especially, to themselves (Frankel 1989). As a consequence, the degree of autonomy the researchers have within the organization, in terms of self-dependent decision-making, impacts the effectiveness of legal regulations and regulations that are based on self-commitment to a formal or informal CoC.

When researchers enjoy a high level of autonomy, they are less pressured to involve others in their decisions and actions. Less involvement from the public reduces the amount of information concerning the behavior of the individual researcher that is available publicly. This leads to a bigger information asymmetry between the individual researchers, on the one hand, and their peers and the public, on the other (Langfred and Moye 2004). The information deficit restricts the possibility of monitoring the researchers' behavior and limits the chances of sanctions being imposed in the case of unlawful conduct. Thus, the more autonomy the individual researchers enjoy in their workplace, the less effective legal regulations will be in restricting individual research behavior.

With a high level of autonomy, regulations based on the researchers' self-commitment to a CoC become more effective (Silver 2005). Analogously to the principle of congruency in management theory, researchers can only be held accountable for their own decisions and actions. Acting according to the CoC (to which the researchers have committed themselves) is an option for them, solely because they have sufficient autonomy in the relevant areas (McDonald and Nijhof 1999). With rising autonomy, the researchers increasingly carry the burden of justifying their actions to themselves. Accordingly, their intrinsic motivation to act according to the CoC becomes relevant (Dubinsky and Loken 1989; Ferrell and Gresham 1985). Thus, higher levels of autonomy lead to more effective behavioral restriction based on self-commitment to a formal or informal CoC.

**H3** The higher the level of autonomy that a researcher enjoys,

(a) the lower will be the effectiveness of legal regulations in restricting individual research behavior and
(b) the higher will be the effectiveness of self-commitment to a code of conduct in restricting individual research behavior.

The competition within the research community also affects the degree to which legal regulations, and, respectively, regulations by self-commitment to a CoC, are able to restrict the scope of research behavior. Even though legal regulations might always be functional, they might become more effective in a situation of high competition. In such situations, a researcher attaches a high degree of importance to his or her reputation relative to those of his or her peers (Wernerfelt and Montgomery 1986). Unlawful acts might give a researcher a competitive advantage, which would have a negative impact on the relative position of other researchers. However, if this type of behavior were reported, the defector might suffer negative consequences. Reporting a defecting colleague is socially accepted, as the sanction is seen less as a punishment, and more as a measure used to balance out the competitive advantage the defector was seeking to gain by breaking the law (Bormann 1975; Jensen 1987). The stronger the competition, the more likely it will be that unlawful acts by competitors will be reported to authorities (Jensen 1987). Potential defectors will anticipate this, and will tend to

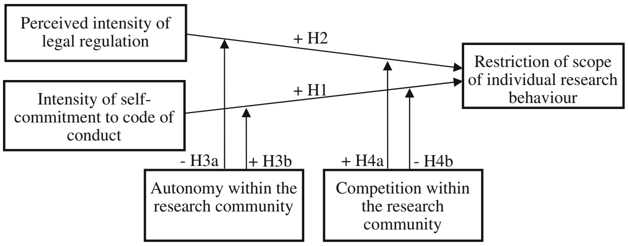


**Fig. 1** Model and hypotheses

abstain from illegal behavior. Moreover, stronger competition forces the members of the research group to exert pressure on individual researchers to perform better and, thus, contribute more to the overall performance of the research group (McCoy 2000). To document their own performance, the individual researcher has to provide information on the decisions made and the behavior shown in the workplace (Hyman 1987). This requirement to document performance makes it easier for authorities to control and punish in the case of misconduct. Thus, rising levels of perceived competition lead to more effective behavioral restriction through legal regulation.

At the same time, with rising competitive pressure the researchers become more tolerant when evaluating their own behavior against the backdrop of the formal or informal CoC to which they have committed themselves.

**H4** The higher the level of competition among researchers,

(a) the higher will be the effectiveness of legal regulations in restricting individual research behavior, and
(b) the lower will be the effectiveness of self-commitment to a code of conduct in restricting individual research behavior.

From the hypotheses, we formulate the following causal model (see Fig. 1).

## A Multi-method Approach

The model presented is based on an analysis of the state-of-the-art literature and includes latent variables that represent multidimensional constructs which need further clarification. If the empirical content of the core building blocks and the causal links between them remain abstract, a model is of no use for deducing practical and relevant recommendations for action. Unfortunately, this often happens in the field of management science. However, according to the idea of evidence-based research (Morrell 2008), we take a first step of engaging in a qualitative survey to clarify the content of the constructs. Based on a better understanding of the content of the latent variables and the causal links between them, our research then engages in a second step of testing the proposed hypotheses. Both the interview guidelines and the survey can be obtained from the authors.

### The Qualitative Survey

To capture a variety of contexts (Linton and Walsh 2008a), we interviewed two researchers employed by a university, and two employed by privately held companies. One of the academics holds a post-doctoral position, while the second is a full professor. The interviewees from the business sector are an R&D manager in a well-established research-based venture, and an entrepreneur of a start-up, respectively. Two interviews were conducted in Vienna (Austria) and two in Twente (the Netherlands). For reasons of consistency and comparison, the interviews were guided. They were recorded, transcribed, and content analyzed following the system proposed by Mayring (2010).

### The Quantitative Survey

#### *Sample*

Data were collected via an online survey that was sent out to 1,400 randomly selected members of the Australian Nanotechnology Network. The survey was open for 10 days. 153 invitations to participate were returned as undeliverable. Out of the remaining 1,247 nanotechnology researchers, 90 completed the survey. This represents a response rate of 7.2 %. While saving resources for both the interviewee and the interviewer, low response rates are a typical negative aspect of online surveys (Fricker and Schonlau 2002). Yanez et al. (2010) report a slightly higher response rate for their online survey of nanotech researchers and evaluate it as acceptable according to the findings of a meta-analysis by Manfreda et al. (2008). As our data do not show any severe non-response bias (Rogelberg and Stanton 2007), we conclude that the response rate does not hamper the validity of our results.

The sample is composed of experienced researchers: 53.3 % have between 1 and 4 years experience, and 43.4 % more than 4 years. Among the respondents, 38.6 % are PhD students, 32.8 % are assistant professors/lecturers, 11.4 % are associate professors/senior lecturers, and 17.1 % are full professors/readers. Apart from a slight over-representation of senior staff, we have covered all levels of academic researchers.

#### *Operationalization*

To operationalize the constructs, we applied reflective scales that were analyzed using principal components analysis with varimax rotation. The results indicate that the scales are reliable.

**Table 1** Validity and correlation coefficients

| | % Var. exp.; $\alpha$ | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|---|
| (1) Restriction | 84.00; 0.902 | 1.000 | | | | | |
| (2) Consequences legal | 69.34; 0.779 | −0.043 | 1.000 | | | | |
| (3) Detection legal | 63.78; 0.803 | 0.397** | −0.027 | 1.000 | | | |
| (4) Consequences formal CoC | 79.01; 0.874 | −0.029 | 0.603** | 0.104 | 1.000 | | |
| (5) Detection formal CoC | 68.21; 0.809 | 0.423** | −0.090 | 0.794** | −.029 | 1.000 | |
| (6) Stakeholder view | 68.71; 0.904 | 0.297** | 0.146 | 0.268* | 0.199 | 0.298** | 1.000 |

* $p < .05$; ** $p < .01$; $n = 90$

Restriction of the scope of research behavior (restriction) was measured using a self-developed scale that taps into whether the researcher is restricted in terms of the topics, methods, and materials they can use within their research. The three-item scale explains 84 % of the variance, with a Cronbach's alpha of 0.904.

To study the impact of legal rules, and, respectively, *formal* CoC, we drew on the scales of "detection of behavior" and "consequences of behavior" from the work of Tyler and Blader (2005), and adapted them to reflect the academic context. While each of the four constructs had reliable measurements (% variance explained and Cronbach's $\alpha$, see Table 1), we found that the scales for "detection," respectively, the scales for "consequences" correlated highly with each other, thus indicating that legal rules and formal CoC may be strongly linked. Based on this finding, we adapted our research approach.

Now, the construct of detection was calculated by combining the items from legal rules and formal CoC. Based on a six-item scale, the construct explains 67.66 % of the variance, with a Cronbach's $\alpha$ of 0.902. We also measured the consequences of violating behavior irrespective of whether legal regulations or *formal* CoC were violated (consequences). Based on a four-item scale, the construct explains 67.26 % of the variance, with a Cronbach's $\alpha$ equal to 0.825.

The construct of self-restriction to an *informal* CoC was measured using an adapted version of the "stakeholder view" in the Perceived Role of Ethics and Social Responsibility (PRESOR) scale (Shafer et al. 2007). The dimension reflects the importance that a researcher assigns to ethics and social responsibility beyond mere performance, and was adapted to reflect the research context. The six-item scale explains 68.71 % of the variance and has a Cronbach's $\alpha$ of 0.904.

Finally, we measured "autonomy" based on items from the Work Design Questionnaire by Morgenson and Humphrey (2006). The nine-item scale explains 72.27 % of the variance and has a Cronbach's $\alpha$ of 0.949.

Competition was measured using a self-developed scale that reflects the degree of competition a researcher perceives both within and outside his or her organization. The four-item scale explains 53.8 % of the variance, and has a Cronbach's $\alpha$ of 0.681.

### Overview of the Results of the Quantitative Analysis

The correlation coefficients (see Table 1) indicate that the detection of violations (detection legal, detection formal CoC) and the stakeholder view restrict the scope of research behavior, while the consequences of a violation do not seem to have an impact. The high correlation between the consequence variables and the detection variables indicates that these constructs might belong together conceptually. Indeed, a second round of factor analyses revealed that detection and consequences both load onto one factor, irrespective of whether they are based on legal regulations or formal CoC.

An OLS regression on "restriction of research behavior" shows that detection and self-restriction both restrict the scope of individual research behavior (see Table 2). A sample split on the median of "autonomy", and, respectively, "competition," shows the contextualized results.

## Results and Discussion

### On the Relationship Between Legal Regulation and CoC

While we assumed a clear differentiation between legal regulations and CoC, our research shows an even more differentiated picture: The qualitative and quantitative analyses suggest that CoCs differ in their effects based on whether they are formal (e.g., promoted by the research institute) or informal (e.g., rooted in the researchers' recognition of the interests of third parties when doing research). Support for this notion is given by the empirical pattern that formal legal regulations and formal CoCs are highly correlated, both with regards to their perceived consequences in the case of detection and the probability of detection, while self-commitment to informal ethical rules

**Table 2** Regression on "Restriction", standardized coefficients

| | Full model | Autonomy high | Autonomy low | Competition high | Competition low |
|---|---|---|---|---|---|
| (Constant) | | | | | |
| Job experience | 0.099 | −0.143 | 0.413** | 0.073 | 0.231 |
| Gender | −0.092 | 0.053 | −0.236# | −0.044 | 0.020 |
| Age | −0.069 | 0.012 | −0.266 | −0.023 | −0.159 |
| Detection | 0.378** | 0.270 | 0.533*** | 0.507*** | 0.147 |
| Consequences | −0.165 | −0.205 | −0.065 | −0.094 | −0.337# |
| Stakeholder View | 0.230* | 0.210 | 0.164 | 0.197 | .309# |
| | df = 89 | df = 43 | df = 43 | df = 46 | df = 41 |
| | adj. $R^2 = .189$ | adj. $R^2 = .016$ | adj. $R^2 = .503$ | adj. $R^2 = .230$ | adj. $R^2 = .057$ |
| | $F = 4.451$** | $F = 1.118$ n.s. | $F = 8.258$*** | $F = 2.773$**″ | $F = 1.209$ n.s. |

n.s. = not significant

# $p < .1$; * $p < .05$; ** $p < .01$; *** $p < .001$; $n = 90$

seems to be an independent construct. The congruence between formal legal regulations and a formal CoC can also be seen in the qualitative part of the research, in that both types of formal regulation are seen as rather distant to nanotechnology research and abstract.

## Legal Regulations, Formal CoC, and the Restriction of Individual Research behavior

We expected that legal regulations would tend to restrict the scope of individual research behavior, as detected violations would result in (substantial) costs to the researchers. Our quantitative findings support the notion that, in particular, the potential detection of misconduct is likely to reduce the scope of a researcher's behavior.

Nevertheless, the qualitative results, both from the university and in the commercial context, suggest that legal regulations and formal CoCs are perceived as rather weak. One reason is that existing formal regulations tend to revolve more around occupational safety rather than nanotechnology, in particular. Another reason may be that formal regulation can be circumvented.

A first reason for the weak impact of legal regulations and formal CoCs may be that researchers perceive an indirect influence from legal regulations on nanotechnology research. For example, researchers have to adhere to laboratory safety regulations (e.g., lab safety levels ML 1–4), which determine the authorization of research and the use of laboratory equipment. These safety regulations are seen as measures that have the potential to restrict the scope of individual research behavior. In addition, a distinction is being made between laboratories used for organic chemistry and those for inorganic chemistry. Therefore, the type of laboratory restricts the type of research behavior that is possible.

Second, examples show that researchers can circumvent the restrictions that they are subject to through the security regulations of their own laboratories. Research that cannot be carried out in their own laboratories can be performed in those of partner organizations. This division of labor can be initiated by means of outsourcing (active), or by taking part in a program that has already specified that the work will be divided among the participants (passive). In one of the cases studied here, a large research program involved animal testing that was carried out at another research institute. In such situations, where certain research behavior is ruled out in one jurisdiction, outsourcing or taking part in an international project can lead to inefficient law enforcement. In sum, laboratory regulations are thus not seen as effective measures for reducing researchers' leeway to engage in opportunism. In addition, the interviewees were of the opinion that legal regulations may not always be efficient in restricting individual research behavior, as they will always lag behind the latest developments.

## Self-commitment to an Informal CoC and the Restriction of Individual Research Behavior

We expected that the more researchers were self-committed to a formal or informal CoC, the more they would restrict the scope of their own individual research behavior. Our quantitative evidence suggests that the recognition of third-party interests, in particular, can lead to restrictions in research behavior.

This finding is supported by our qualitative analysis. In general, the interviewed researchers did not perceive their work as being directly affected by a *formal* CoC. Reasons given were that they saw formal CoCs as being rather abstract and not well-communicated at their place of research. However, they did commit themselves rather unconsciously to *informal* CoCs, which evolved from with their research communities: according to the researchers interviewed, there is a tacit understanding between them and their colleagues regarding what should and what should not be done within nanotechnology research.

Such informal CoCs build upon ethical values that are perceived as central to the research community. In this regard, the researchers listed honesty and transparency concerning their research results as maxims they committed themselves to. In addition, it was found that it is a central ethical principle not to harm anyone either during the process of doing research or with the results of the research behavior, as it is the researchers' common goal to contribute to the solution of current problems without crossing moral boundaries. Nevertheless, the researchers were aware of the difficulties of making these choices. For example, research on explosives could contribute to building more powerful bombs, but also to building tunnels.

According to the findings, if researchers do not adhere to these informal CoCs, they will be confronted with moral stigma and a loss in reputation, which can result in exclusion from the research community. Therefore, their intense, but rather unconscious self-commitment to an informal CoC, which has evolved from discourse within the research community and the society, exerts a powerful constraining influence on the behavior of the interviewed researchers.

### Researchers' Autonomy and the Restricting Effects of Legal regulations and Codes of Conduct

We hypothesized that autonomy would reduce the effect of legal regulations, while strengthening the effect of an informal CoC. Our quantitative results suggest that, under a high degree of autonomy, no mechanism reduces the scope of research behavior, whereas under a low degree of autonomy, it is particularly the detection of violations of formal rules that restricts research behavior.

Qualitative evidence suggests that autonomy is particularly high for university professors. Upon receiving a chair, they usually present a sketch of future research ideas. After receiving a chair, internal control measures are restricted to informal discussions with the dean and their colleagues. For externally funded projects, contracts that define the research goals and the employed methods restrict the autonomy of researchers. However, due to a lack of expertise and background knowledge, the supervision of research behavior by the funding institution or sponsoring firm is often limited to an ex post control, based on a report. This check, in most cases, is focused on the economic rather than the ethical dimension of the research project.

At privately held companies, the degree of autonomy enjoyed by researchers is seen as being more restricted, by hierarchical company structures and economic pressure. This is especially true in small and young ventures, where the portion of R&D activities that are devoted to "research" rather than "development" is rather small (Shane 2004). The more applied the research, the less open the topical foci and the more defined the research processes are, and thus the researcher has less autonomy. Thus, university-based researchers and company-based researchers differ in their assessment of their degree of autonomy.

We expected that high levels of autonomy for individual researchers would result in less restriction on individual research behavior due to legal regulations. In general, the interviewees agreed: the more autonomy the researchers have to develop and pursue their own research agendas, the less possibility there is for control, which is the prerequisite of effective legal regulation. In academic research, the only formal checks the interviewees face are annual job evaluation interviews with their superior (e.g., the dean) and laboratory journals, which are diaries of what the researchers do in their laboratories.

Looking at the history of how the practice of keeping laboratory journals came into existence—it was developed by the scientific community itself to make research, and specifically the processes involved, more reproducible—the disadvantages of using them as the basis for legal regulation become apparent: the researchers anticipate that their journals will be used to evaluate their behavior (e.g., they may keep two journals). Especially at universities, such journals are often not kept as assiduously as is necessary for them to be effective control instruments. Even if they were, reproducibility is not a suitable criterion for evaluating ethical research behavior, as—apart from an honest documentation and communication of the research activities—reproducibility also depends on the influence of unobserved variables.

In a way that is more differentiated than our quantitative findings suggest, all of our interviewees stressed the crucial role of tacit rules within the scientific community that are binding for all members. The adherence to an informal CoC seems to be motivated by the individual researcher trying to maintain a good reputation in the research community. Reputation is the most valuable capital that researchers have in their communities because it communicates their status and position, based on their perceived potential. Hence, the danger of damaging one's reputation in the community through actions that are detrimental to the community's norms strongly restricts individual research behavior. While a large part of this mechanism is self-governed by the individual researcher, it is supported by the controlling actions of the research group: The vast majority of research in nanotechnology is conducted in teams. The members of a research team mutually control each other, because their own reputation is at risk in the case of group work.

This informal CoC influences the individual researchers' behavior when facing any given decision. The more leeway they have to engage in opportunism, the more chances there are for them to make the "right" decision based on the informal CoC. At the same time, high levels of autonomy imply that there are reduced limitations on tapping the potential of nanotechnology research. Accordingly, the interviewees highlight that researchers need a high level of autonomy, to have the flexibility to act according to the norms to which they have committed themselves.

### Competition and the Restricting Effects of Legal Regulations and Codes of Conduct

We hypothesized that competition would enhance the effect of legal regulations, while reducing the effect of informal CoCs. Our quantitative results suggest that, under a high degree of competition, legal regulations do tend to become more effective, and self-commitment does not become ineffective.

This is mirrored by our qualitative results. The interviewed nanotechnology researchers evaluate the competition within the research field as very intense. Additionally, there is massive hierarchical pressure within academic and business organizations. Commonly, researchers in lower level positions directly compete for positions at higher levels. The competitive processes involved in applying for research grants and external funding intensify the competitive pressure on nanotechnology researchers. Thus, there is strong competition for funds and for slots in high-end journals. Overall, the interviewees describe the competition in the field as "fierce but friendly".

Based on the theoretical reasoning put forth above, we expected that intense competition would strengthen the restricting effect of legal regulations on individual research behavior. In line with this hypothesis, some of the interviews with nanotechnology researchers showed that intense competition might make it more likely that whistleblowers would appear on the scene. Under intense competition, the inclination to tolerate the misconduct of colleagues is reduced as researchers feel they are suffering the consequences themselves: The competitive advantage gained from unlawful or unfair behavior is seen as being decisive in the selection processes for grants, for gaining a higher position or for other resources.

We assumed that the restricting effect on individual research behavior due to self-commitment to an informal CoC would be lower when the competition within the research community was high. The interviewees report that, in nanotechnology research, competition loosens the ties of ethical norms. They feel that researchers have difficulty in competing successfully when they stick closely to the CoC. Especially, they note that the communication of findings may be biased by "optimistic publishing" and "overselling". Another practice, which can be regarded as unfair, is the formation of "citation circles," which may gain importance under greater competition. However, in general, the researchers report that their ethical principles do not change because of rising competition. Nevertheless, they are more tempted to test out the limits of their maxims, i.e., they are less strict with themselves when they evaluate their behavior against the informal CoC, which in turn reduces the practical relevance of self-regulation.

## Concluding Remarks

Nanotechnology has attracted much attention in the literature and in practice, due to its scientific and economic potential, but there has been surprisingly little debate on political and ethical issues, focusing on the behavior of the individual researcher. We investigated the relative effectiveness of legal regulations and of self-regulation via self-commitment, in shaping the scope of research behavior at the level of the individual researcher. We also highlighted the influence of institutional contingencies (autonomy and competition) on the restraining effects of legal regulations and self-regulation via self-commitment. We focused on the researcher as the key agent, which is an under-researched aspect in the literature on nanotechnology regulation. Based on a discussion of the state-of-the-art literature, we proposed a model and refined the concepts using a qualitative study.

Legal regulations and self-commitment to informal CoCs restrict the scope of individual research behavior. Nevertheless, the strength of their impact is contingent on the context of the researcher. The fear of detection is particularly effective in situations of low autonomy or high competition, while self-commitment is particularly effective in situations of low competition.

The limitations of this research need to be addressed: this study provides a snapshot of the relative effectiveness of legal regulations and of self-regulation via self-commitment in shaping the scope of research behavior at the level of the individual nanotechnology researcher. However, researchers' attitudes toward nanotechnology are not static. Further, the empirical base needs to be strengthened so as to make more differentiated statements. For example, nanotechnology researchers at a lower hierarchical level may find competition much harder and their autonomy to be less, which could have an impact on the effectiveness of governance systems at that level. Pertaining to a more differentiated empirical basis, it would be interesting to explore different types of research institutes.

Future research should focus on the question of how the concept of organizational culture shapes the ethical behavior of employees in general, and of researchers in particular (Siegrist et al. 2007). The actions of peers, stakeholders, policy analysts, advocacy groups, and freelance futurists will also influence researchers' behavior regarding this enabling technology. Further social science research is therefore needed to better understand how social processes may impact researchers' perceptions of the regulation of their research behavior. To delve into the historical, social, and political reality affecting ethically and socially responsible research processes, we suggest integrating survey research with other research methods, such as experiments and projective methods.

Notwithstanding the above limitations, our findings have two major implications for the design of a regulatory regime for nanotechnology research: first, the mechanisms employed have to account for the different natures of basic research and applied research. While basic research is driven by the curiosity of the researchers and is thus a creative process which is contingent in its development and opens in its results, applied research takes previous findings from basic research as a defined starting point, and aims at developing marketable applications. Tight legal regulations would cut back the possible directions that could be followed in basic research. This would pose a potential threat to the development of nanotechnology research, because the contingent nature of basic research makes it impossible to predict its findings. A strong legal restriction on basic research in nanotechnology, which the regulators could only formulate based on guesswork, could potentially eliminate findings which might be valuable starting points for applied, follow-up research. Or, as Kitcher (2007, p. 181) puts it: "Vulgar democracy has its own form of myopia: Ordinary citizens—and their public representatives—usually lack any firm grasp on the scientific possibilities." While the great amount of autonomy afforded to researchers in basic research further diminishes the effectiveness of legal regulations, it intensifies the regulative power of self-commitment to the (informal) CoC. Therefore, the individual researchers' behavior in basic research into nanotechnology cannot be effectively restricted by legal regulation, but only by self-commitment to (informal) CoC.

In contrast, the well-defined starting point and clear aims of applied research could make the prediction of potential benefits and dangers comparatively easy. Competition is especially intense within applied research, as it is often a race for profits, generated through designing applications that succeed in the market. With the first-mover's advantage being especially relevant in markets for high-tech products, time becomes a decisive factor, which in turn implies more intense competition. In view of the negative effect of competition intensity on the effectiveness of individual researchers' self-commitment to (informal) CoCs, the necessity of tighter legal regulations on applied research in nanotechnology becomes apparent.

The second major implication refers to the necessity to account for the specific contexts of different niches of nanotechnology research. The development of a general regulatory framework for the whole of nanotechnology research seems an infeasible approach. The immense heterogeneity of nanotechnology research only allows for the design of regulations within separate niches, most of which are defined by the disciplines from which the researchers or research objects originated.

Even if our findings do not allow us to propose a general regulatory regime for the whole field of nanotechnology research, we give clear and practically relevant recommendations for fostering ethical research behavior within nanotechnology, depending (1) on the autonomy and competition within the niche and (2) on whether the nature of the research activity is basic or applied. Our results give theoretically rooted and practically relevant insights for nanotechnology researchers and for the policy-makers who design governance mechanisms for nanotechnology.

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