Articles

Delay of Gratification in Children

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To function effectively, individuals must voluntarily postpone immediate gratification and persist in goal-directed behavior for the sake of later outcomes. The present research program analyzed the nature of this type of future-oriented self-control and the psychological processes that underlie it. Enduring individual differences in self-control were found as early as the preschool years. Those 4-year-old children who delayed gratification longer in certain laboratory situations developed into more cognitively and socially competent adolescents, achieving higher scholastic performance and coping better with frustration and stress. Experiments in the same research program also identified specific cognitive and attentional processes that allow effective self-regulation early in the course of development. The experimental results, in turn, specified the particular types of preschool delay situations diagnostic for predicting aspects of cognitive and social competence later in life.

FOR ALMOST A CENTURY THE INFANT HAS BEEN CHARACTERized as impulse-driven, pressing for tension reduction, unable to delay gratification, oblivious to reason and reality, and ruled entirely by a pleasure principle that demands immediate satisfaction (*1*). The challenge has been to clarify how individuals, while remaining capable of great impulsivity, also become able to control actions for the sake of temporally distant consequences and goals, managing at least sometimes to forgo more immediate gratifications to take account of anticipated outcomes. The nature of this future-oriented self-control, which develops over time and then coexists with more impetuous behaviors, has intrigued students of development, who have made it central in theories of socialization and in the very definition of the "self" (*2*). Such goal-directed self-imposed delay of gratification is widely presumed to be important in the prevention of serious developmental and mental health problems, including those directly associated with lack of resilience, conduct disorders, low social responsibility, and a variety of addictive and antisocial behaviors (*3–9*).

To explain how people manage to exercise self-control, concepts like "willpower" or "ego strength" are readily invoked, although these terms provide little more than labels for the phenomena to which they point. Some people adhere to difficult diets, or give up cigarettes after years of smoking them addictively, or continue to work and wait for distant goals even when tempted sorely to quit, whereas others fail in such attempts to better regulate themselves in spite of affirming the same initial intentions. Yet the same person who exhibits self-control in one situation may fail to do so in another, even when it appears to be highly similar (*6*). The research program reviewed here addresses the nature of these individual differences, the psychological processes that underlie them, and the conditions in which they may be predictable.

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Overview

We review findings on an essential feature of self-regulation: postponing immediately available gratification in order to attain delayed but more valued outcomes. Studies in which 4-year-old children attempt this type of future-oriented self-control reveal that in some laboratory situations individual differences in delay behavior significantly predict patterns of competence and coping assessed more than a decade later (*10*). Experiments in the same laboratory situations have identified specific cognitive and attentional processes that allow the young child to sustain goal-directed delay of gratification even under difficult, frustrating conditions (*11*).

We begin with a summary of major individual differences associated with this type of self-regulation early in life, and the long-term developmental outcomes that they predict. Then we examine the specific processes that seem to underlie effective self-imposed delay of gratification in young children, as revealed by the experimental studies. These results, in turn, pointed to the types of preschool delay situations diagnostic for predicting aspects of cognitive and social competence in adolescence. Finally, we consider the development of the child's understanding of self-control and the concurrent links found among components of self-regulation in children with behavioral problems.

Measuring Self-Control: From Choice to Execution

Two complementary methods were used to investigate delay of gratification in the research program reviewed here. Initially, preferences for delayed, more valuable versus immediate but less valuable outcomes were studied as choice decisions. In this approach, individuals choose under realistic conditions among outcomes that vary in value and in the expected duration of time before they become available. Sets of such choices were given to people from a wide range of sociocultural backgrounds, family structure, and economic circumstances (*5, 12*). As expected, these choices are affected predictably by the anticipated delay time and the subjective value of the alternatives. For example, preferences for delayed rewards decrease when the required time for their attainment increases and increase with the expectation that the delayed outcomes will occur (*13, 14*). The choice to delay (i) increases with the values of the delayed rewards relative to the immediate ones; (ii) increases with the subject's age; and (iii) is susceptible to a variety of social influences, including the choice behavior and attitudes that other people display (*3, 5, 11, 13*). Choices to delay were related significantly to a number of personal characteristics assessed at about

the same time. For example, children who tend to prefer delayed rewards also tend to be more intelligent (*13*), more likely to resist temptation (*15*), to have greater social responsibility (*9, 16*), and higher achievement strivings (*17*). The obtained concurrent associations are extensive, indicating that such preferences reflect a meaningful dimension of individual differences, and point to some of the many determinants and correlates of decisions to delay (*18*).

As efforts at self-reform so often attest, however, decisions to forgo immediate gratification for the sake of later consequences (for example, by dieting) are readily forgotten or strategically revised when one experiences the frustration of actually having to execute them. Because intentions to practice self-control frequently dissolve in the face of more immediate temptations, it is also necessary to go beyond the study of initial decisions to delay gratification and to examine how young children become able to sustain delay of gratification as they actually try to wait for the outcomes they want. For this purpose, a second method was devised and used to test preschool children in the Stanford University community (*19, 20*).

In this method, the experimenter begins by showing the child some toys, explaining they will play with them later (so that ending the delay leads to uniform positive consequences). Next, the experimenter teaches a game in which he or she has to leave the room and comes back immediately when the child summons by ringing a bell. Each child then is shown a pair of treats (such as snacks, small toys, or tokens) which differ in value, established through pretesting to be desirable and of age-appropriate interest (for example, one marshmallow versus two; two small cookies versus five pretzels). The children are told that to attain the one they prefer they have to wait until the experimenter returns but that they are free to end the waiting period whenever they signal; if they do, however, they will get the less preferred object and forgo the other one. The items in the pair are selected to be sufficiently close in value to create a conflict situation for young children between the temptation to stop the delay and the desire to persist for the preferred outcome when the latter requires delay. After children understand the contingency, they are left on their own during the delay period while their behavior is observed unobtrusively, and the duration of their delay is recorded until they terminate or the experimenter returns (typically after 15 minutes). With this method, "self-imposed delay of gratification" was investigated both as a psychological process in experiments that varied relevant features in the delay situation and as a personal characteristic in studies that examined the relation between children's delay behavior and their social and cognitive competencies.

A recent follow-up study of a sample of these children found that those who had waited longer in this situation at 4 years of age were described more than 10 years later by their parents as adolescents who were more academically and socially competent than their peers and more able to cope with frustration and resist temptation. At statistically significant levels, parents saw these children as more verbally fluent and able to express ideas; they used and responded to reason, were attentive and able to concentrate, to plan, and to think ahead, and were competent and skillful. Likewise they were perceived as able to cope and deal with stress more maturely and seemed more self-assured (*21, 22*). In some variations of this laboratory situation, seconds of delay time in preschool also were significantly related to their Scholastic Aptitude Test (SAT) scores when they applied to college (*23*). The demonstration of these enduring individual differences in the course of development, as well as the significance attributed to purposeful self-imposed delay of gratification theoretically, underline the need to understand and specify the psychological processes that allow the young child to execute this type of self-regulation in the pursuit of desired outcomes.

Effects of Attention to the Rewards

Theoretical analyses of the delay process have assumed for almost a century that the individual's attention during the delay period is especially important in the development of the ability to delay gratification (*1, 24*). William James, noting a relation between attention and self-control as early as 1890, contended that attention is the crux of self-control. Beginning with Freud, it has been proposed that attention to the delayed gratifications in thought, mental representation, or anticipation provides the mechanism that allows the young child to bridge the temporal delay required for their attainment. When children become able to represent the anticipated gratifications mentally, it was reasoned, they become able to delay for them by focusing on these thoughts or fantasies, thereby inhibiting impulsive actions. Some learning theorists also have speculated that the cognitive representation of rewards allows some sort of anticipatory or symbolic covert reinforcement that helps sustain effort and goal-directed behavior while external reinforcement is delayed (*11*).

In spite of the fact that rewards were given paramount importance in psychological attempts to explain the determinants of behavior, their role in the delay process had remained mostly speculative because of the difficulty of objectively studying thoughts about rewards, particularly in young children. To study how their thinking about the rewards affects self-imposed delay, preschool children in the Stanford University community were assessed in several variations of the self-imposed delay situation described earlier. If thinking about the rewards facilitates delay, then children who are exposed to the rewards or encouraged to think about them should wait longer. The first study varied systematically whether or not the rewards were available for attention while the children were waiting (*19*). For example, in one condition they waited with both the immediate (less preferred) and the delayed (more preferred) rewards facing them, exposed. In a second condition, both rewards were also present but obscured from sight (covered), and in two other conditions either the delayed reward only or the immediately available reward was exposed during the delay period. The results were the opposite of those the investigators predicted: attention to the rewards consistently and substantially decreased delay time instead of increasing it. Preschool children waited an average of more than 11 minutes when no rewards were exposed, but they waited less than 6 minutes on average when any of the rewards were exposed during delay.

To test the effects of thinking about the rewards more directly, in a second study different types of thoughts were suggested to orient the children's attention with regard to the rewards (*20*). The results showed that when preschoolers were cued to think about the rewards when waiting, delay time was short, regardless of whether the objects were exposed or covered (Fig. 1). When distracting ("fun") thoughts were suggested, children waited for more than 10 minutes, whether or not the rewards were exposed. On the other hand, when no thoughts were suggested, delay time was greatly reduced by reward exposure, confirming the earlier findings. Distracting thoughts counteracted the strong effects of exposure to the actual rewards, allowing children to wait about as long as they did when the rewards were covered and no thoughts were suggested. In contrast, when the rewards were covered and the children were cued to think about them, the delay time was as short as when the rewards were exposed and no distractions were suggested (*25, 26*). Thus, the original prediction that attention and thought directed to the reward objects would enhance voluntary delay was consistently undermined.

Observation of children's spontaneous behavior during the delay process also suggested that those who were most effective in

sustaining delay seemed to avoid looking at the rewards deliberately, for example, covering their eyes with their hands and resting their heads on their arms. Many children generated their own diversions: they talked quietly to themselves, sang, created games with their hands and feet, and even tried to go to sleep during the waiting time. Their attempts to delay gratification seemed to be facilitated by external conditions or by self-directed efforts to reduce their frustration during the delay period by selectively directing their attention and thoughts away from the rewards (*11*). However, it also seemed unlikely that sheer suppression or distraction from the frustration caused by the situation is the only determinant of this type of self-control. Indeed, when certain types of thoughts are focused on the rewards they can facilitate self-control substantially, even more than distraction does, as the next set of experiments found.

From Distraction to Abstraction

The results so far show that exposure to the actual rewards or cues to think about them undermine delay, but the studies did not consider directly the possible effects of images or symbolic representations of rewards. Yet it may be these latter types of representation—the images of the outcomes, rather than the rewards themselves—that mediate the young child's ability to sustain delay of gratification (*1, 27*). To explore this possibility, the effects of exposure to realistic images of the rewards were examined by replicating the experiments on the effects of reward exposure with slide-presented images of the rewards. It was found that although exposure to the actual rewards during the delay period makes waiting difficult for young children, exposure to images of the rewards had the opposite effect, making it easier. Children who saw images of the rewards they were waiting for (shown life-size on slides) delayed twice as long as those who viewed slides of comparable control objects that were not the rewards for which they were waiting, or who saw blank slides (*27*). Thus, different modes of presenting rewards (that is, real versus symbolic) may either hinder or enhance self-control.

To test more directly the effects of the cognitive representations of rewards on delay behavior, preschool children were taught to transform "in their heads" the stimuli present during delay (real rewards or pictures of them) by turning real rewards into pictures and pictures into real rewards in their imagination (*28*). How the children represented the rewards cognitively was a much more potent determinant of their delay behavior than the actual reward stimulus that they were facing. For example, children facing pictures of the rewards delayed almost 18 minutes, but they waited less than 6 minutes when they pretended that the real rewards, rather than the pictures, were in front of them. Likewise, even when facing the real rewards they waited almost 18 minutes when they imagined the rewards as if they were pictures.

This pattern of results may reflect two different aspects of reinforcing (rewarding) stimuli that, in turn, may have completely different effects on self-control behavior. Consistent with earlier work (*29*), we hypothesized that stimuli can be represented both in an arousing (consummatory) and in an abstract (nonconsummatory) informative manner. In an arousing representation, the focus is on the motivating, "hot" qualities of the stimulus that tend to elicit completion of the action sequence associated with it, such as eating a food or playing with a toy. In an abstract representation the focus is on the more informative, "cool," symbolic aspects of the stimulus, for example, as in a cue or reminder of the contingency or reason for delaying the action sequence associated with it (*30*).

Specifically, it was suggested to one group of children that they could focus their thoughts on the arousing qualities of the rewards (such as the pretzel's crunchy, salty taste), and to another group of children that they could focus on the reward's abstract qualities and associations (by thinking about pretzel sticks, for example, as long, thin brown logs). Two other groups were given the same type of suggestions as to how they could think while waiting, but directed at comparable control objects that were not the rewards (Fig. 2). When encouraged to focus on the abstract qualities of the rewards, children waited an average of more than 13 minutes but they waited less than 5 minutes when the same type of thoughts were directed at the comparable objects that were not the rewards, suggesting that the abstract representation of the actual reward objects provides more than just distraction.

The longest mean delay time (almost 17 minutes) occurred when the suggested thoughts were also about control objects but with regard to their arousing qualities (for example, children waiting for marshmallows who had been cued to think about the salty, crunchy taste of pretzels). Thus, while hot ideation about the rewards made delay difficult, such ideation directed at comparable objects that are not the rewards for which one is waiting may provide very good distraction. The results support the view that attention to the rewards may have either a facilitating or an interfering effect on the duration of delay, depending on whether the focus is arousing or abstract.

The experimental results, taken collectively, help specify how young children can become able to sustain self-imposed delay gratification for substantial periods. Delay is difficult for the preschooler when the rewards are exposed, unless distractions are provided or self-generated. Suggestions to think about the rewards, or attention to them, can facilitate or interfere with delay, depending on whether the rewards are represented in ways that lead to a focus on their arousing or abstract features. An abstract focus on the rewards can help self-imposed delay even more than comparable distractions; an arousing focus makes delay exceedingly difficult. How the child represents the rewards cognitively in this regard, rather than whether they are exposed physically or as images, crucially influences the duration of delay.

Preschool Delay Conditions for Predicting Long-Term Developmental Outcomes

On the basis of the experimental research reviewed so far, it also becomes possible to specify the types of preschool delay conditions in which the child's behavior will be more likely to predict relevant long-term developmental outcomes. The significant links noted earlier between delay of gratification at age 4 years and adolescent competence did not take account of the particular delay conditions. When the rewards are exposed, delay becomes highly frustrative for preschoolers, so that to sustain their goal-directed waiting they must use effective strategies, for example, by distracting themselves or by representing the rewards cognitively in an abstract, "cool" way. When preschoolers are not given strategies for sustaining delay but the rewards are exposed, they must generate and execute such strategies on their own to delay, and therefore their behavior should reveal most clearly individual differences in this type of competence. To the degree that this ability is stable and has enduring consequences for adaptation, we expected that preschool delay time when the rewards are exposed and no strategies are suggested would be diagnostic for predicting relevant developmental outcomes. In contrast, when the rewards are obscured, delay behavior was not expected to reflect children's ability to generate effective self-control strategies because that situation does not require the use of such strategies.

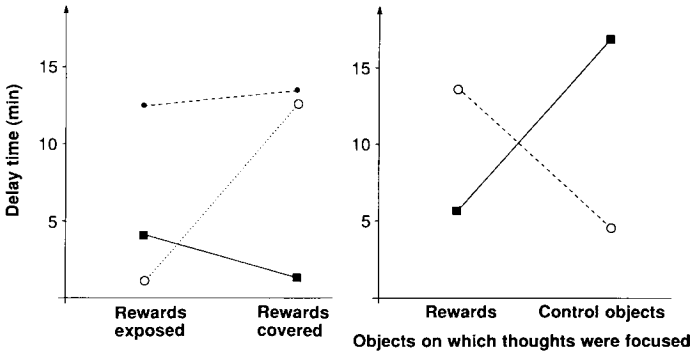

Fig. 1. (**Left**) Average delay time shown by 52 Stanford preschoolers when different types of thoughts were suggested (●, fun thoughts; ■, thoughts about the rewards; ○, no thoughts suggested) and the rewards were exposed or covered [based on figure 4 in (*20*)]. **Fig. 2.** (**Right**) Delay time as a function of objects on which thoughts were focused (rewards versus comparable control objects) and type of cognitive representation in thoughts [arousing (■) versus abstract (○)]. All 48 Stanford preschool children were facing the exposed rewards [data are from table 1 in (*30*)].

These expectations were supported in another follow-up study of the Stanford preschool children, in which we increased the sample of respondents so that the role of conditions could be analyzed in relation to long-term outcomes (*23*). To obtain a more objective measure of cognitive academic competences and school-related achievements in adolescence, we also included Scholastic Aptitude Test (SAT) scores. In conditions in which the rewards were exposed and no strategies were supplied, those children who delayed longer as preschoolers were rated in adolescence by their parents as significantly more attentive and able to concentrate, competent, planful, and intelligent. They also were seen as more able to pursue goals and to delay gratification, better in self-control, more able to resist temptation, to tolerate frustration, and to cope maturely with stress. Beyond parental ratings, in the same conditions SAT scores were available for 35 children, and both their verbal and quantitative SAT scores were significantly related to seconds of preschool delay time. The linear regression slope predicting SAT verbal scores from seconds of preschool delay time was 0.10 with a standard error of 0.04; for predicting SAT quantitative scores, the slope was 0.13 with a standard error of 0.03. The correlations were 0.42 for SAT verbal scores and 0.57 for SAT quantitative scores. In contrast, individual differences in delay behavior when the rewards were obscured did not reliably predict either parental ratings or SAT performance.

The significant correlations between preschool delay time and adolescent outcomes, spanning more than a decade, were relatively large compared to the typically low or negligible associations found when single measures of social behavior are used to predict other behaviors, especially over a long developmental period (*6*). On the other hand, although the obtained significant associations are at a level that rivals many found between performances on intelligence tests repeated over this age span (*31, 32*), most of the variance still remains unexplained. The small size of the SAT sample dictates special caution in these comparisons and underlines the need for replications, especially with other populations and at different ages.

As previously noted, preschool delay time in the diagnostic condition was significantly related not only to academic abilities of the sort assessed by the SAT but also to other indices of competence. Even after statistically controlling for SAT scores, preschoolers who had delayed longer were later rated by parents as more able to cope with a number of social and personal problems, suggesting that the relation between preschool delay time and later parental judgments is not completely attributable to school-related competencies as measured by the SAT.

The causal links and mediating mechanisms underlying these long-term associations necessarily remain speculative, allowing many different interpretations. For example, an early family environment in which self-imposed delay is encouraged and modeled also may nurture other types of behavior that facilitate the acquisition of social and cognitive skills, study habits, or attitudes which may be associated with obtaining higher scores on the SAT and more positive ratings by parents. It also seems reasonable, however, that children will have a distinct advantage beginning early in life if they use effective self-regulatory strategies to reduce frustration in situations in which self-imposed delay is required to attain desired goals. By using these strategies to make self-control less frustrating, these children can more easily persist in their efforts, becoming increasingly competent as they develop.

Of course, the self-regulatory strategies that have been described are not the only ones useful for sustaining goal-directed delay and effort. The particular strategies required depend on the type of delay situation, for example, self-imposed versus externally imposed delay (*26*). During the delay process children may use a variety of strategies, including self-instructions, rehearsal of the specific contingencies for goal attainment while avoiding an arousing focus on the rewards themselves, and self-monitoring of progress (*11*). Related research in variations of the delay of gratification situation with young children showed the value for self-control of specific, carefully rehearsed and elaborated plans for inhibiting temptations to terminate goal-directed efforts (*33*). Such plans are used spontaneously, in varying degree, even by preschool children. Similar self-regulatory strategies have been identified in research on the acquisition of cognitive skills for mastery of other tasks requiring self-control, like reading (*34*) and impulse inhibition (*35*). It is also plausible that the specific competencies necessary for effective self-regulation are a component of a larger ability or set of abilities involving both cognitive and social knowledge and skills. Whereas self-regulatory competencies in the pursuit of goals are not even considered as a factor in traditional conceptions and tests of intelligence (*36*), they are directly relevant to more recent attempts to devise a theory of social intelligence that integrates findings from cognitive, social, and developmental psychology to thoroughly reconstruct the analysis of intelligent behavior (*37*).

The Development of Knowledge about Effective Self-Regulatory Strategies

In the course of development, children show increasing understanding and awareness of the strategies that facilitate various kinds of self-control. In a sample of middle-class children in the Stanford community, from preschool through grade six, the children's knowledge of the strategies that might help during the delay process were assessed (*38*). The overall results indicate that 4-year-olds often prefer the least effective strategies for self-imposed delay, thereby inadvertently making self-control exceedingly difficult for themselves. For example, they significantly prefer to expose the rewards during the delay period and to think about them (for example, "because it makes me feel good"), thus defeating their own effort to wait. Within a year, most children understand and choose more effective strategies. They soon prefer to obscure the temptations and consistently reject arousing thoughts about them as a strategy for self-control. At that age many begin to recognize the problem of increased temptation produced by thinking about the arousing attributes of the rewards and try to self-distract ("just sing a song"). They also start to see the value of self-instructions, focusing on the contingency and reiterating it ("I'll wait, so I can get the two

marshmallows instead of one" or "I'll say, 'do not ring the bell.' . . . If you ring the bell and the teacher comes in, I'll just get that one"). The self-control rule that does not seem to become available until some time between the third and sixth grades requires recognition of the value of abstract rather than arousing thoughts, suggesting possible links between the development of this type of understanding and the child's achieving operational thought in the Piagetian sense (*39*).

Extensions to Older Children at Risk

The research described so far specified some of the strategies that facilitate delay experimentally and summarized the development of children's growing knowledge and understanding of those strategies. However, the links between children's knowledge of effective strategies, their spontaneous use of such strategies when attempting to control themselves in the pursuit of delayed goals, and their success in sustaining delay remained unexamined. The delay process in older children with behavior problems, such as aggressiveness, conduct disorders, or hyperactivity, has been surprisingly unstudied, although these are the very individuals for whom effective attention deployment and sustained delay of gratification are assumed to be especially difficult (*40*). So far, research on delay of gratification has concentrated on preschool children without known developmental risks. Therefore, a recent study extended the delay paradigm to a population of older children, described as having a variety of social adjustment difficulties, such as aggressiveness and withdrawal (*41*).

In this sample, ages 6 to 12 years, assessed in a summer residential treatment facility, children's knowledge of self-control processes was significantly correlated with duration of their self-imposed delay. For example, those who knew that an abstract rather than an arousing representation would make waiting easier also delayed longer. Similarly, the children's spontaneous attention deployment during the delay period was significantly related to their actual delay time: as the delay increased, those who were able to sustain self-control spent a higher proportion of the time distracting themselves from the frustrative situation than did those who terminated earlier. Even when controlling statistically for the effects of verbal intelligence, the relations among knowledge of self-control, spontaneous use of effective delay strategies, and duration of delay remained significant. In addition, those individuals who scored higher on these indices of self-control in the delay situation, especially when the rewards were exposed, also were rated as significantly less aggressive throughout the summer (*42*). The overall findings obtained with older children at risk indicate that the cognitive attentional strategies that allow effective delay of gratification, as identified in the earlier experiments, also seem to be used spontaneously by individuals who delay longer.

Summary

Taken collectively, the results from the research programs we reviewed specify some of the cognitive processes that underlie this type of delay of gratification early in life. Whether or not attention to the rewards, or distraction from them, is the better strategy for sustaining self-control depends on how the rewards are represented cognitively. A focus on their arousing features makes self-control exceedingly difficult; a focus on their more abstract, informative features has the opposite effects. Moreover, the type of cognitive representation generated can overcome, and reverse, the effects of exposure to the rewards themselves.

Significant links were found between self-control behavior as measured in this paradigm and relevant social and cognitive outcomes years later. The experimental research allowed identification of the conditions in which these long-term relations were most clearly visible. The child's spontaneous understanding of effective self-regulatory strategies also was found to develop in a clear age-related sequence. Finally, delay of gratification in the same paradigm with older children at risk showed the expected concurrent relations to knowledge of effective self-control strategies and spontaneous attention deployment while trying to exercise self-control. An unanswered question now is whether or not teaching delay of gratification skills and strategies of the sort identified to those who lack them, early in life, would in fact reduce later developmental risks such as school failure. Postponing gratification sometimes may be an unwise choise, but unless individuals have the competencies necessary to sustain delay when they want to do so, the choice itself is lost.

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Molecular Recognition and Metal Ion Template Synthesis

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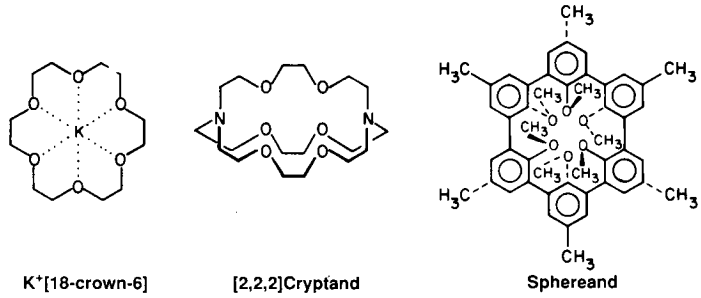
Methods for the design and synthesis of ligands intended to be specific for a metal ion have been a recent chemical development. This article describes how this process can be inverted so that the specifics of the coordination environment around the metal ion can be used as a template in large-scale ligand synthesis. The synthesis of macrobicyclic ligands for ferric ion has been accomplished by using active esters of catechol ligands in which catecholate coordination to iron is a prelude to the organic chemical reactions that link the coordination subunits together into one ligand system surrounding a central metal ion coordination site. The lanthanide(III) ions, which are among the most labile metal ions known, have coordination numbers of 8 or higher, and thus their encapsulation into a macrobicyclic structure is a challenging problem. Lanthanide amine complexes have been used as metal templates in the synthesis of such macrobicyclic lanthanide complexes. There is evidence that such a complex is inert to exchange in aqueous solution.

MOLECULAR RECOGNITION IN BIOLOGICAL SYSTEMS OCcurs at a level of sophistication and beauty that is rarely matched in the laboratory. Efforts to understand these complex processes on a molecular level have led chemists to study synthetic receptors, that is, small (<2000 daltons) molecules designed to complex a particular substrate, be it organic or inorganic (*1*). The synthetic analogs are held together by covalent bonds such that a cavity is formed, with appropriate electron donor (or acceptor) groups directed toward the proposed substrate binding site. In contrast, a protein or polynucleotide utilizes noncovalent interactions to enforce the tertiary structure necessary for substrate binding. The limited number of receptor-substrate interactions present in a synthetic model system, combined with the relatively small receptor size, simplifies the study of molecular recognition. In addition, systematic variation of fundamental receptor properties, for example, cavity size, can be achieved through synthesis.

Perhaps the most familiar and illustrative examples of such studies emanate from the pioneering work of Pedersen (*2*), Cram (*3*), and Lehn (*4*), who studied the effect of cavity size, shape, and rigidity on the binding of alkali metals with oxygen donor hosts, such as those shown in Scheme 1. The macrocyclic crown ethers incorporate



K⁺[18-crown-6] [2,2,2]Cryptand Sphereand

Scheme 1

etherial oxygen donor groups within a macrocyclic ring. The macrobicyclic cryptands are cage molecules that form an ellipsoidal cavity of well-defined shape. The sphereands incorporate phenolic ether oxygen donors into rigid macrocyclic rings that are preorganized for metal binding. Thermodynamic evaluation of the binding of alkali metals to these receptors shows a dramatic correlation of cavity dimension with preferred ion size (*5*).

Cram has emphasized the importance of host preorganization in

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